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FINAL REPORT

SHUTTLE CRYOGENICS SUPPLY SYSTEM OPTIMIZATION STUDY

VOLUME III

TECHNICAL REPORT

Sections 10 Through 12

CONTRACT NAS9-11330

Prepared for Manned Spacecraft Center
by
Manned Space Programs, Space Systems Division

LOCKHEED MISSILES & SPACE COMPANY, INC.
A SUBSIDIARY OF LOCKHEED AIRCRAFT CORPORATION

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SHUTTLE CRYOGENICS SUPPLY SYSTEM OPTIMIZATION STUDY. VOLUME III, TECHNICAL REPORT, SECTIONS 10 THROUGH 12 FINAL REPORT

LOCKHEED MISSILES AND SPACE COMPANY, INC.
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FINAL REPORT
SHUTTLE CRYOGENIC SUPPLY SYSTEM
OPTIMIZATION STUDY

VOLUME III
TECHNICAL REPORT

Sections 10, 11, and 12

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FOREWORD

This Final Report provides the results obtained in the Shuttle Cryogenics Supply System Optimization Study, NAS9-11330, performed by Lockheed Missiles & Space Company (LMSC) under contract to the National Aeronautics and Space Administration, Manned Spacecraft Center, Houston, Texas. The study was under the technical direction of Mr. T. L. Davies, Cryogenics Section of the Power Generation Branch, Propulsion and Power Division. Technical effort producing these results was performed in the period from October 1970 to June 1973.

The Final Report is published in eleven volumes*:

Volume I	– Executive Summary
Volumes II, III, and IV	– Technical Report
Volume VA-1 and VA-2	– Math Model – Users Manual
Volume VB-1, VB-2, VB-3, and VB-4	– Math Model – Programmer Manual
Volume VI	– Appendixes

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Section 12 in Volume III contains the List of References for Volumes I through IV.

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Section 10

INTEGRATED SYSTEM TRADEOFF STUDIES

The number of cryogenic subsystems being considered for the Space Shuttle leads to the examination of ways that the subsystems can be integrated. Through integration, some overall system weight reduction can be expected. But, more importantly, the reduction in complexity obtained by combining cryogenic storage and supply systems will likely result in impressive gains in system reliability, maintainability, operational flexibility, and finally a reduction in program and unit costs. To achieve the full benefits of this integration, a logical display of the various possible subsystem combinations was established, followed by selection and analysis of reasonable candidates.

The number and variety in sizes of the various cryogenic subsystems aboard the Space Shuttle Orbiter make integration a complex problem. A huge array of combinations for integration is mathematically possible, particularly when interconnected lines and use of common heat-exchangers or other equipment are considered.

10.1 CANDIDATE SYSTEM APPROACHES

A set of guidelines was used to establish a matrix of possible combinations. First, the primary mode of integration is defined to be a common storage tank, with the use of connecting lines as a subalternative case. Second, due to the impracticality of insulating the orbit injection system tanks for long-term storage, they were considered for integration only in cascade tank arrangements or for use as low-pressure accumulators. Third, integration of subsystems requiring high-purity fluids was subject to this limitation.

The original matrix, which was used to establish the baseline for integration potential of cryogenic systems, is shown in Fig. 10.1-1. A list of the subsystems with the maximum and minimum cryogen load and flowrates is shown in Table 10.1-1. Seven basic subsystems (shown at the top of the matrix) were

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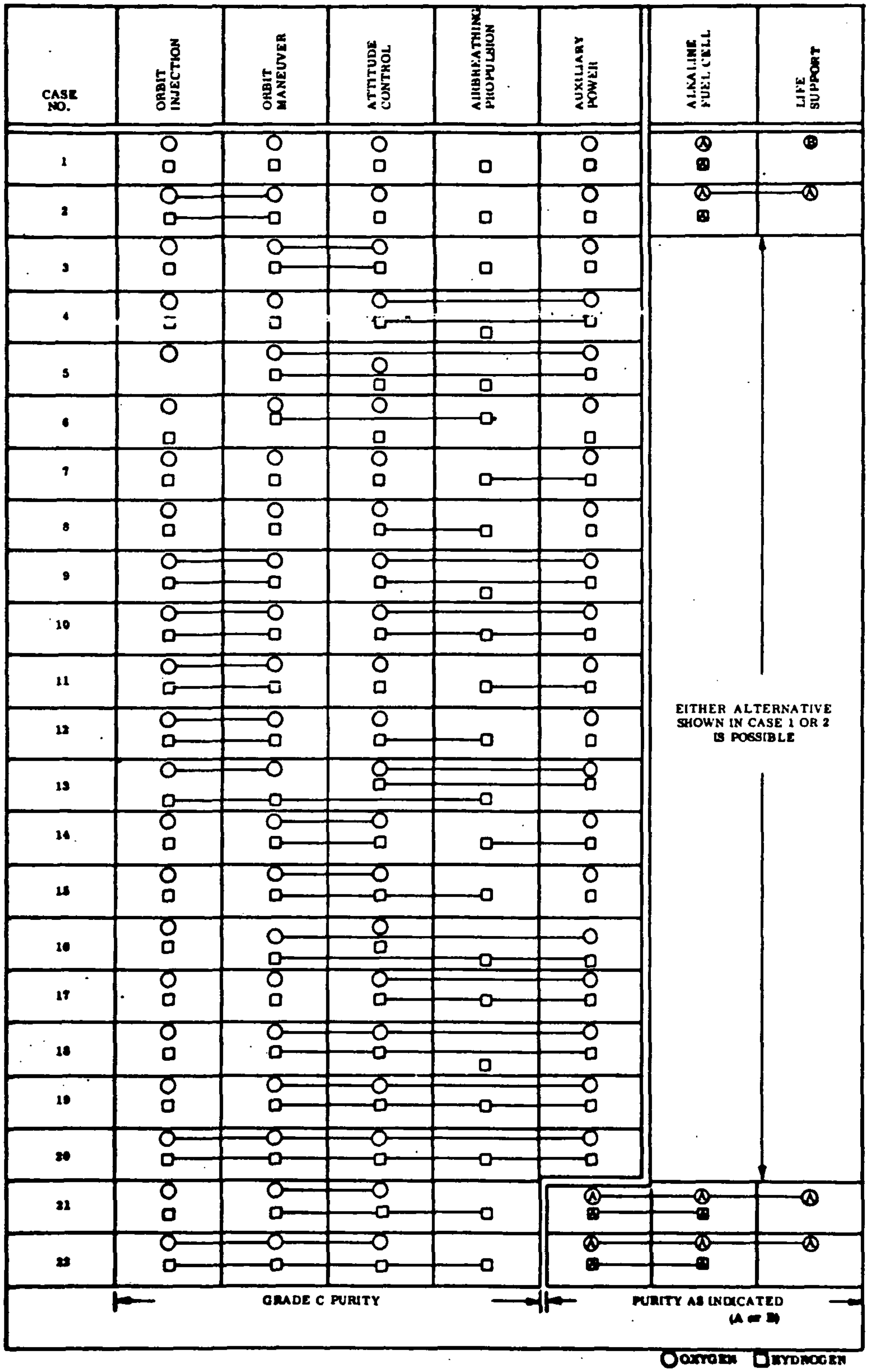

Fig. 10.1-1 Potential Modes of Integration

Table 10.1-1

SUBSYSTEM CRYOGENIC FLUID REQUIREMENTS

		O_2 QUANTITY (LB)	O_2 FLOW RATE (LB/SEC)	H_2 QUANTITY (LB)	H_2 FLOW RATE (LB/SEC)	WHEN USED
OIPS	MAX. MIN	532,000 360,000	2,374 593	86,000 60,000	396 99	EARLY
OMPS	MAX MIN	27,000 18,300	38 13	5,400 3,700	8 4	EARLY LATE
ACPS	MAX MIN	6,900 2,000	26 2	2,150 500	7.0 0.5	MOST EARLY SOME CONT. SOME LATE
ABE	MAX MIN			2,800 1,500	5.0 1.0	LATE
FUEL CELL	MAX MIN	1,450 730	.0053 .0008	175 90	.0006 .0001	CONTINU- OUSLY
APU		500 100	.25 .02	525 100	.29 .02	EARLY LATE
LIFE SUPPORT		83 8	.0001 .00004			CONTINU- OUSLY

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considered as major contributors to the variety of combinations. Other systems that can contribute to various degrees of integration are: purging and inerting systems, valve actuation systems, and active reentry thermal protection systems. Serious integration analysis of these systems was not conducted, because (1) the first two consist of inert fluids that tend to cause them to be categorized separately from the oxygen and hydrogen used in the other systems, and (2) the third system has not yet been identified as a mainline approach for the shuttle. At the time the matrix was established, it was deemed prudent to identify integration combinations that recognized the potential problems associated with the use of multigrades of oxygen and hydrogen.

Cases 1 through 20 show the possible modes for integrating the systems using Grade C fluids; the range is from no integration (Case 1) to complete integration (Case 20). Only two alternatives are shown for the fuel-cell reactants and life support supply, since these systems are separate to ensure purity. Because the use of Grade A oxygen in the life support system is practical, this mode of integration is indicated.

Additional modes of integration are possible if the higher purity fluids are used in other systems. However, the auxiliary power system is the only system with small enough propellant requirements to be considered economically acceptable. The resulting modes are shown as Cases 21 and 22, which complete the matrix.

Purity is one consideration that limited the modes of integration presented above. One method of overcoming this limitation is to provide an onboard purification system to upgrade the purity of propellant grade fluids for use in the life-support system and as fuel-cell reactants. Early in the study, however, it was considered practical to utilize Grade C cryogens for both the fuel cell and life support supply. This resulted in extending the matrix to include additional modes of integration as shown in Fig. 10.1-2 and, therefore, several cases were added to the list so that fuel cell and life support systems would be integrated.

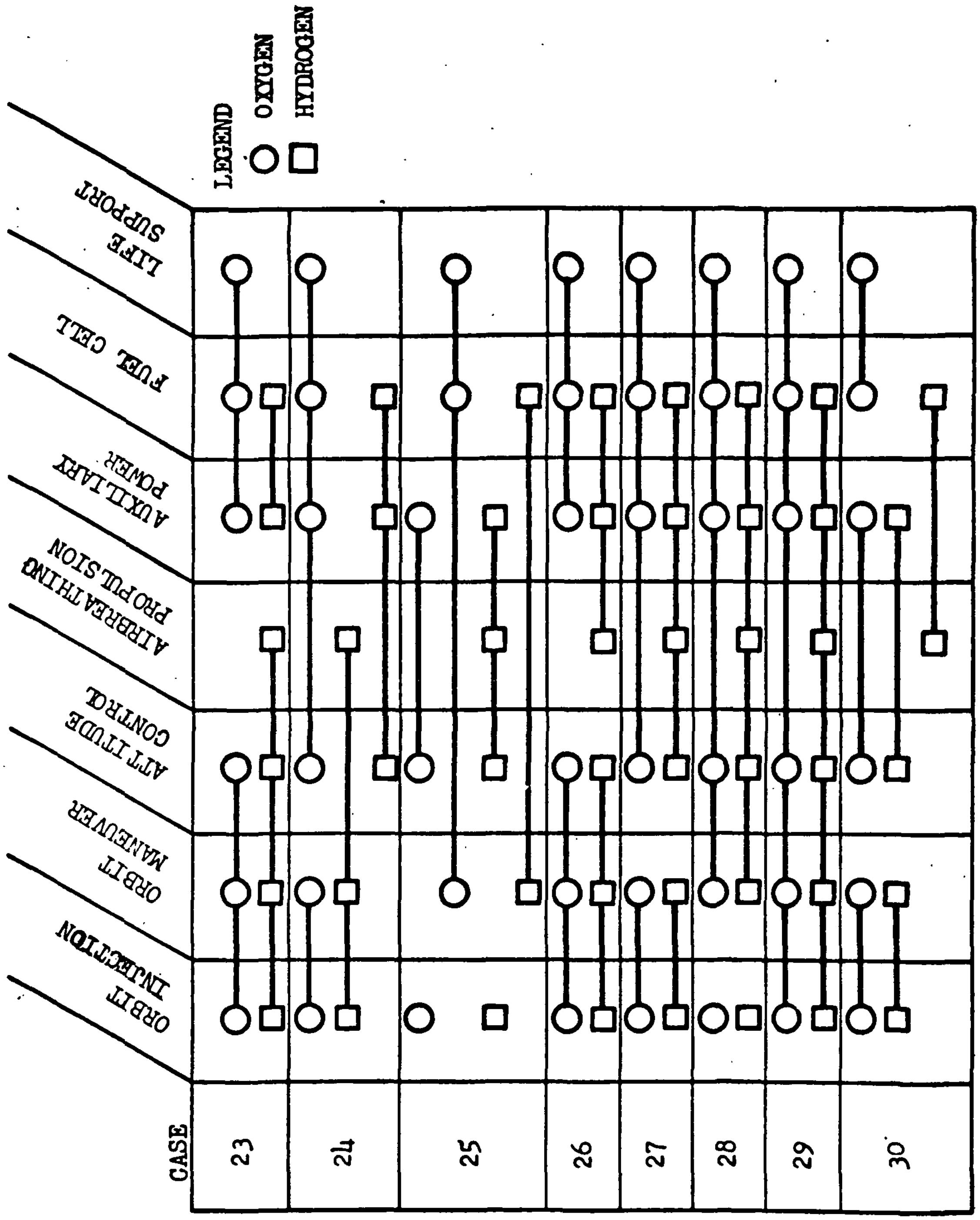

Fig. 10.1-2 Additional Modes of Integration

The matrix represents combinations of the primary mode of integration, which is common storage tanks. The circles indicate oxygen tanks and the squares indicate hydrogen tanks. Lines connecting these circles and squares represent the common storage of the cryogens for the particular subsystem indicated.

10.2 SELECTION OF CANDIDATE CONCEPTS

The matrices, shown in Figs. 10.1-1 and 10.1-2, represent only the storage tank mode of integration. Several other modes of integration were considered. Six modes were established to represent the items that may play significant roles in the integration process; these items are: storage, lines, tank pressure control, thermal control, fluid control, and fluid conditioning.

The various concepts and combinations that resulted for each case listed in Figs. 10.1-1 and 10.1-2 are shown in Table 10.2-1. Six modes of potential integration are shown along the top of the table, and comments regarding integration methods, which apply to these modes, are listed for each case. Thus, almost all combinations and concepts for the integration of the cryogenic subsystems on the Space Shuttle are listed.

Each case (shown in the matrix of Table 10.2-1) was reviewed, and at least one representative block-diagram flow chart was prepared for the significantly different cases. These are presented in Figs. 10.2-1 through -20. The flow charts show a basic mode of integration of each of the six elements listed (Table 10.2-1), along with alternates that appeared worthy of evaluation. For example, starting with Case 2, which calls for the orbital injection system (OIS) and the orbital maneuver system (OMS) to be integrated, one can see from the flow chart (Fig. 10.2-1) that the primary mode is to consider the OIS propellant to be stored separately from the OMS propellant. Also, alternate integration modes for tank pressure control and propellant transfer are shown.

Flow diagrams for each case were prepared except where one case is a combination of one or more preceeding cases, (e.g., no flow diagrams were prepared for Case 9, because it is basically a combination of Cases 2 and 4). Case 11 is a combination of Cases 2 and 7. Case 12 is a combination of Cases 2 and 8. Case 13 is a combination of Cases 2, 4, and 6. Case 14 is a combination of Cases 3 and 7. Case 17 is a combination of Cases 4 and 10. Case 21 consists of two parts: Case 15 and a new flow diagram representing the integration of the APU fuel cell and the EC/LSS. Case 22 consists of a

combination of Case 20 without the APU and the second part of Case 21. Case 23 is a combination of Case 20 and the second part of Case 21.

In considering Cases 24 to 30, complete statements of potential integration modes were included in the matrix of Table 10.2-1 rather than referring back to combinations of other cases. To some extent, this repeats some of the previously listed integration concepts; however, it was felt that if reference back to other concepts were continued, confusion soon would exist and the matrix would become useless. Therefore, for each Case (24 to 30) in which all cryogenic subsystems are considered in one form of integration or another, a potential integration concept was stated for each of the six elements.

At this point, a comprehensive representation of all reasonable integration concepts has been displayed. The process of selecting appropriate combinations for further analyses is described next.

Table 10.2-1

APPROACH TO COMPOSITION OF INTEGRATED SYSTEM CANDIDATES

Case	MAJOR SUBSYSTEM ELEMENTS					
	Storage	Lines	Tank Pressure Control	Thermal Control	Fluid Control	Fluid Conditioning
1	No Integration					
2	Integrate OIS and OMS					
	• Tanks cascaded • None	If separate OMS and OIS engines are used: • No line integration • If cascaded tanks, integrate lines to points where OMS engine is TEED off If OMS engine is a throttled OIS engine: • If cascaded tanks are used, the lines for OMS engine and OIS engine are identical • If tanks are separate, lines are separate • None	If Cascaded tanks and same engine: • Use same pressurization system for OMS as for OIS, either cascaded or with isolation valving *If tanks are separate:* • Use separate pressurization systems • Use OIS tank residuals for OMS tank pressurization or prepressurization • None	• Use OIS residuals to cool OMS tanks and/or lines • Put OMS tanks inside OIS tanks • None	• With integrated lines, use all same valves, regulators, etc. • With separate lines, use separate valves • Fluid acquisition in OMS propellant tanks • *Acceleration for propellant orientation* • None	• None
3	Integrate OMS and ACPS					
3.1	OMS Engine is Entirely Separate From ACPS					
	• Store ACPS propellants in OMS propellant tanks • Resupply ACPS propellant tanks from OMS tanks • None	• Utilize propellant in OMS lines for ACPS functions • Utilize OMS lines for ACPS accumulators • Use OMS lines to supply ACPS conditioning system in areas where applicable • None	• Supply OMS tank pressure with ACPS gas • accumulators • Use same pressurization system supply for OMS and ACPS • None	• Place ACPS tanks inside OMS tanks • Cool OMS lines with ACPS propellants • None	• Use same acquisition devices if propellants are in the same tank • Use ACPS to orient propellant for OMS burn • Use OMS circulation pumps and lines, if any, to resupply ACPS tanks • None	• Use OMS pumps to resupply high pressure fluid to ACPS tanks or accumulators • Use OMS engines to supply heat to ACPS propellants • None
3.2	OMS Engines Use ACPS Pressure and/or Thermally Conditioned Propellants					
	• Store ACPS propellants and OMS propellants in the same tank • None	• Use OMS lines to supply propellants to ACPS and OMS pressure/thermal conditioner • Use OMS lines for accumulators • None	• Supply tank pressure from ACPS high pressure accumulators • Supply tank pressure from external pressure supply • None	• Multilayer insulation • Vent gases to cool lines • None	• Use acquisition devices in common tank • None	• Common pump for OMS and ACPS engines. Liquid to OMS engine, and to heat exchanger for storage in ACPS high pressure accumulators • None

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Table 10.2-1

APPROACH TO COMPOSITION OF INTEGRATED SYSTEM CANDIDATES (Cont)

Case	MAJOR SUBSYSTEM ELEMENTS					
	Storage	Lines	Tank Pressure Control	Thermal Control	Fluid Control	Fluid Conditioning
4	Integrate ACPS and Auxiliary Power					
	• Store ACPS and APU propellants subcritically in the same tanks • Store ACPS and APU propellants supercritically in the same tanks • Transfer from subcritical ACPS tanks to supercritical APU tanks • Transfer from supercritical ACPS to supercritical APU • APU propellants drawn from ACPS accumulators • None	• Use same lines where possible • None	• Pressurize APU tanks with ACPS accumulator gas • If ACPS and APU are stored subcritically use common He pressurization • Pressurize subcritical ACPS from supercritical APU • Pressurize (condition) supercritical ACPS and/or APU with gas stored in accumulators • None	• Pass ACPS propellant by APU tank for heat interception • None	If common subcritical storage is used • Use same acquisition system • Use same valves and feed control If same supercritical storage is used • Use same valves and feed control • None	• Use common pumps • Use common heat exchanger • Condition (pressurize) fluid in ACPS and/or APU tanks with warm high pressure accumulator gas • Use common accumulators • None
5	Integrate Orbit Maneuver System (OMS) and Auxiliary Power Unit (APU)					
	• Store APU propellants in OMS tanks (subcritical) • Resupply subcritical APU tanks from OMS • Resupply supercritical APU tanks from OMS – From high pressure pumps – Resupply subcritically and heat	• Use OMS lines as storage accumulators • Use OMS lines as distribution lines for APU where feasible • None	• Pressurize with He • Pressurize OMS from supercritical APU • Pressurize with OMS pump pressure	• Chill OMS lines by circulating APU supply through tubes on lines • Circulate OMS propellant by APU tank • None • Place APU tanks inside OMS tanks	• If common storage use same acquisition devices	• Pressurize APU with OMS pump • Use OMS pump and heat exchanger to supply APU if they can be operated independently from thruster • Independent APU pump • Independent APU heat exchangers
6	Integrate OMS and Airbreathing Propulsion LH_2 Tanks (Liquid Engine Delivery)					
	• Store airbreathing LH_2 requirements in OMS tankage; 38% increase in OMS LH_2 tankage volume (subcritical storage)	• Common feed mainfold from tankage to ABP tee • Separate feed lines compatible with each system flow rate	• Use same pressurization system compatible with each system with common repressurization stored GH_2 • Use line chill-down recirculation as common prepressurization with common repressurization feed to tankage	• Integrating the tankage requires "one" TCU • The ABP boost pump can be utilized as a chill-down pump to ensure LH_2 delivery to both OMS and ABE. The chilldown function will serve as prepressurization	• Common acquisition system, with common tank outlet for both functions. Liquid quantity ensures compatible outlet • Common valving with isolation of systems as required	• Common HX • Use ABP boost pump for prestart fluid conditioning • Separate HX to meet specific needs of each system

Table 10.2-1

APPROACH TO COMPOSITION OF INTEGRATED SYSTEM CANDIDATES (Cont)

Case	MAJOR SUBSYSTEM ELEMENTS					
	Storage	Lines	Tank Pressure Control	Thermal Control	Fluid Control	Fluid Conditioning
7	Integrate Airbreathing Propulsion and APU LH_2 Tankage					
	● Store the APU LH_2 requirements in the airbreathing tankage; 20% increase in ABP tankage volume (subcritical storage)	● Common feed manifold from tankage to APU tee, ABP line size governs ● Separate feed lines compatible with each system flow rates ● Common tank exit manifold with separate feed lines to applicable system	● Common thermal conditioning system to maintain tank pressure control. During ABP operation pressurization maintained from ABE bleed	● Common thermal condition system	● Acquisition system required for APU; made common to accommodate each system ● Separate valving after tank outlet ● Common valving with ABP requirements governing	● Common HX ● Separate HX to meet specific needs of each system
8	Integrate Airbreathing Propulsion and ACPS LH_2 Tankage					
	● Combine the LH_2 supply requirements for both the ABP and ACPS (subcritical storage) common tankage doubles either volume	● Command feed manifold from tankage ● Common feed lines ● Separate feed lines compatabile with each system	● Common thermal conditioning system to maintain tank pressure control	● Common thermal conditioning system	● Common acquisition system compatible with boost pump of ABE ● Separate valving after tank outlet ● Common valves with ABE requirement governing	● Common HX ● Separate HX to meet specific needs of system
9	Integrate OIS and OMS with Integrated ACPS and APU					
	● Refer to Case 2 for OIS and OMS integration; refer to Case 4 for ACPS and APU integration					
10	Integrated OIS and OMS; Integrated ACPS and APU LO_2; Integrated ACPS, APU and ABP Hydrogen					
	● Refer to Case 2 for OIS and OMS integration ● Refer to Case 4 for ACPS and APU integration of LO_2 ● Store the ACPS, ABP, and APU LH_2 in common tankage subcritically ● Store APU separately (quantity) ● None	● Utilize common tank outlet manifold with ABP flow rate governing design ● Tee off from tank outlet manifold to meet line size requirements and flow rates of individual subsystem	● The thermal conditioning unit for the ABP can maintain adequate tank pressure control to insure LH_2 delivery to all pumps in APU and ACPS	● Common insulation and thermal control system; more efficient LH_2 storage with surface to volume ratio of larger tankage ● ABP boost pump could be utilized to chill lines	● Common containment device for APU and ACPS can also serve for ABP although not required; must be sized for ACPS usage	● None, HX exchanger loads and flow rates not compatible for integration ● ABP boost could be utilized to insure NPSH requirements for ACPS and APU pumping requirements

Table 10.2-1

APPROACH TO COMPOSITION OF INTEGRATED SYSTEM CANDIDATES (Cont)

Case	MAJOR SUBSYSTEM ELEMENTS					
	Storage	Lines	Tank Pressure Control	Thermal Control	Fluid Control	Fluid Conditioning
11	Integrated OIS and OMS; Integrated ABP and APU LH_2					
	• Refer to Case 2 for OIS and OMS integration • Refer to Case 7 for ABP and APU LH_2 integration					
12	Integrated OIS and OMS; Integrated ABP and ACPS LH_2					
	• Refer to Case 2 for OIS and OMS integration • Refer to Case 8 for ABP and ACPS LH_2 integration					
13	Integrated OIS and OMS LO_2; Integrated ACPS and APU LO_2; Integrated OIS, OMS and ABP LH_2					
	• Refer to Case 2 for OIS and OMS LO_2 integration • Refer to Case 4 for ACPS and APU integration • Cascade OIS and OMS tanks and increased volume of OMS tank to accommadate ABP propellant; then refer to Case 6 for OMS and ABP LH_2 integration					
14	Integrated OMS and ACPS; Integrated ABP and APU LH_2					
	• Refer to Case 3 for OMS and ACPS integration • Refer to Case 7 for ABP and APU LH_2 integration					

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Table 10.2-1

APPROACH TO COMPOSITION OF INTEGRATED SYSTEM CANDIDATES (Cont)

Case	MAJOR SUBSYSTEM ELEMENTS					
	Storage	Lines	Tank Pressure Control	Thermal Control	Fluid Control	Fluid Conditioning
15	Integrated OMS and ACPS LO_2; Integrated OMS, ACPS and ABP LH_2					
	• Refer to Case 3 for integration of OMS and ACPS LO_2 • Common tank storage for all LH_2 requirements of OMS, ACPS and ABP. Stored subcritically	• Common tank outlet, port size for the combined flow rate requirements of OMS and ACPS • Common lines to TEE for ABP, continue common lines to TEE for ACPS system propellant conditioning	• With common tank the thermal condition system will maintain adequate tank pressure control during quiescent periods • Active pressurization can be combined by increasing line from OMS engine bleed; with individual feed into common manifold for ABP operational period	• Common insulation system with integrated thermal conditioning system • Cool required subsystem lines with TCU vent gas • Separate thermal control required for ACPS downstream of common OMS and ACPS pump • ABP boost pump requirement can serve to cool other integrated system lines	• Common liquid acquisition system. ABP boost pump could be integrated for ACPS and OMS to insure proper NPSH requirements	• Integrate the ACPS pumping (high-pressure ACPS) requirement with the OMS pumps. Must be capable of meeting both OMS and ACPS requirements or each system individually (pump speed control or throttling problem) • Size the accumulators in ACPS so that during OMS operation no demand is put on pump for ACPS accumulator recharging • After an OMS firing recharge ACPS accumulators to full capability to insure no increased demand on OMS pumping system
16	Integrated OMS and APU LO_2; Integrated OMS, APU and ABP LH_2					
	• Refer to Case 5 for OMS and APU LO_2 integration • Common LH_2 supply tankage for OMS, ABP and APU. Stored subcritically • Store APU separately due to duty cycle at end of mission; pressurization of large ullage for small propellant displacement	• Common tank outlet and lines, TEE off common manifold when required to meet system needs	• Thermal conditioning system with common tankage can maintain adequate pressure control during quiescent periods • Source bleed off OMS pressurization system for OMS operation with common manifold for bleed-off pressurization when ABP in operation. Sized for maximum system demand	• ABP boost pump can be utilized for line chill down of OMS and/or recirculation lines are integrated • Common tankage gives common TCU in which vented gas will maintain chilled line of APU supply to pump	• Common tankage results in common liquid acquisition system • ABP boost pump could be utilized with common manifolding to maintain chilled lines for OMS	• ABP boost pump used to insure NPSH requirements of OMPS • Potential of switching APU drive media to ABP if utilize power pad from engine
17	Integrated ACPS and APU LO_2; Integrated ACPS, APU and ABP LH_2					
	• Refer to Case 4 for ACPS and APU LO_2 integration • Refer to Case 10 for ACPS, APU and ABP LH_2 integration					

Table 10.2-1

APPROACH TO COMPOSITION OF INTEGRATED SYSTEM CANDIDATES (Cont)

Case	MAJOR SUBSYSTEM ELEMENTS					
	Storage	Lines	Tank Pressure Control	Thermal Control	Fluid Control	Fluid Conditioning
18	Integrated OMS, ACPS and APU LO_2 and LH_2					
	• Combined propellant requirement of OMS, ACPS and APU stored in a common tank for each propellant • Separate APU storage requirements	• Common tank outlet with common lines and manifolding with Tee off at applicable points to meet requirements of individual system • Combine and integrate ACPS and APU requirements up to ACPS accumulators (high pressure ACPS)	• Tank pressure control maintained by a common thermal conditioning system with autogenuous pressurization during OMS and ACPS usage	• Common thermal conditioning system with common integrated insulation • TCU can be utilized to chill required lines for the integrated system • Common insulation if ACPS and APU requirements integrated in accumulators	• Common acquisition system sized for OMS requirements	• The ACPS and APU propellants delivered by common pumping system into ACPS accumulators. APU operated from ACPS accumulators • With autogenous pressurization, boost pump of OMS can serve to insure NPSH requirement of the combined ACPS and APU pumping system
19	Integrated OMS, ACPS and APU LO_2; Integrated OMS, ACPS, APU and ABP LH_2					
	• Refer to Case 18 for applicable remarks only additional integration is inclusion of ABP LH_2	• The ABP and OMS lines could be integrated with applicable TEEs, with integration of ACPS and APU due to coincident flow rates • Common tank outlet with complete line integration with applicable branches for individual system requirements	• See Case 18	• See Case 18 • ABP boost pump can be utilized to chill lines of OMS	• Common acquisition system sized for ABP boost pump requirements	• Refer to Case 18 • The ABP boost pump could be utilized to insure NPSH requirements of OMS and an integrated ACPS and APU pumping system
20	Integration of All Systems					
	• The integration of the OIS was limited to cascaded tankage see Case 2	• The conditions of Case 2 coupled with Cases 18 and 19 apply	• Refer to Case 2, 18 and 19	o Refer to Case 2, 18 and 19 for complete system integration		

Table 10.2-1

APPROACH TO COMPOSITION OF INTEGRATED SYSTEM CANDIDATES (Cont)

Case	MAJOR SUBSYSTEM ELEMENTS					
	Storage	Lines	Tank Pressure Control	Thermal Control	Fluid Control	Fluid Conditioning
21	Integrated OMS and ACPS LO_2; Integrated OMS, ACPS, and ABP LH_2; Integrated APU; EPS and EC/LSS					
	• Refer to Case 15 for OMS and ACPS LO_2 integration and OMS, ACPS and ABP LH_2 integration. 1. Store each propellant requirement for all systems in a common tank. Store subcritically. 2. Store supercritically in common tankage.	1. Common tankage permits common outlet drain with integrated fill, vent. 2. The EC/LSS and EPS O_2 can utilize common lines and valving due to compatible pressure and temperature levels of both systems. Sized for combined system flow rates. 3. APU lines separate. 4. Complete line integration with supercritical storage with Tee's to supply combined EC/LSS and EPS requirements.	1. Eliminate GHe pressurization of APU and utilized common thermal system to maintain tank pressure requirements. 2. Supercritical storage eliminates GHe requirements with common thermal conditioning system to maintain tank pressure control.	1. Common tanks dictate common insulation system. 2. Cooling of lines for APU system (pumping) integrated with thermal conditioning system. 3. Common tankage aids in thermal control of bulk propellant.	1. Integrate into our supply tank; then the acquisition device required for APU can be utilized to insure known conditions of supply to EC/LSS and EPS heat exchangers (subcritical storage). 2. Supercritical storage eliminates need for acquisition systems within an integrated tank.	1. The EC/LSS can be fully integrated within a common heat exchanger and regulator system due to pressure and temperature compatibility of both systems. 2. Supercritical storage eliminates pumps from APU. Conditioned by storage and regulators. 3. GHe eliminated from APU to meet requirements of EPS parity.
22	Integrate OIS, OMS, ACPS, and ABE LH_2. Integrate APU, Fuel Cell, and EC/LSS Oxygen.					
	• Refer to case 20 and 21. Same as case 20 except APU is integrated with EC/LSS and EPS as given in case 21.					
23	Integrate OIS, OMS and ACPS O_2 System and OCS, OMS, ACPS and ABE H_2 Systems. Integrate APU, Fuel Cell, and EC/LSS O_2 System and APU, Fuel Cell, H_2 Systems (Same as case 22).					
	1. OIS tanks cascaded with OMS, ACPS propellant stored in OMS tanks. Store ABE fuel in OMS tank. 2. OIS tank cascaded with OMS. ACPS propellant stored in OMS tank. ABE separated. 3. OIS tank separate. OMS, ACPS ABE (fuel) stored in same tank. 4. OIS tank separate. ACPS separate ABE propellant stored in OMS tank. 5. OIS, OMS, ABE, ACPS separate.	1. Use OIS lines for ACPS accumulators. 2. Use OIS lines and tanks for ACPS distribution and feed (low pressure). 3. Tee off OMS line to feed ABE where possible. 4. Use APU lines to feed fuel cell. 5. None.	1. Pressurize with He. 2. Pressurize with gaseous propellants or reactants. 3. Use OIS residuals for OMS, and ABE pressurization. 4. Add heat to reactant tanks from fuel cell. 5. Add heat to reactant tanks from APU. 6. Add heat to fuel cell reactants from ECS system. 7. Use TCU in OMS and ACPS tank.	1. Insulation. 2. Store tanks inside other tanks. 3. Use OIS residuals to cool OMS lines. 4. Use OIS residuals to cool OMS tanks. 5. Use OMS residuals to cool ABE lines and feed system. 6. Use EC heat to condition fuel cell reactant. 7. None integration.	1. Common OMS-ACPS acquisition device. 2. Same valve and lines on OIS and OMS to where the OMS engine is feed-off. 3. Same valves and lines on APU, fuel cell and EC/LSS to where different conditions and use is required. 4. None.	1. Use boost pump to supply OMS and ABE. 2. Use common pump for OMS and ACPS. 3. Use common pump for OMS, ACPS and ABE. 4. Use common pump for APU, fuel cell, and EC/LSS 5. Use common thermal conditioners for APU, fuel cell and EC/LSS. 6. Use common thermal conditioners for fuel cell and EC/LSS. 7. None.

Table 10.2-1

APPROACH TO COMPOSITION OF INTEGRATED SYSTEM CANDIDATES (Cont)

Case	MAJOR SUBSYSTEM ELEMENTS					
	Storage	Lines	Tank Pressure Control	Thermal Control	Fluid Control	Fluid Conditioning
	6. Store APU, fuel cell and EC/LSS (oxygen) in same tanks. 7. APU separate. Fuel cell and EC/LSS (oxygen) stored in same tank. 8. APU, fuel cell, EC/LSS separate. 9. None.					
24	Integrate OIS and OMS and ABE Fuel. Integrate ACPS, APU, Fuel Cell, and EC/LSS Oxygen.					
	1. Cascade OIS propellant through OMS tanks; store ABE fuel in OMS tanks. 2. Cascade OIS propellant through OMS tanks. Store ABE separately. 3. OIS propellant separate. ABE fuel stored in OMS tank. 4. OIS, OMS, ABE separate. 5. Store ACPS, APU, fuel cell, and EC/LSS cryogens in common tanks. 6. ACPS and APU cryogens in common tanks. Fuel cell and EC/LSS in common tanks. 7. ACPS, APU, fuel cell cryogens in common tanks. EC/LSS oxygen separate. 8. ACPS separate. APU fuel cell and EC/LSS cryogens in common tanks. 9. ACPS, APU, fuel cell, and EC/LSS cryogens separate. 10. Transfer from ACPS tanks to fuel cell and to APU tanks on a partial basis. 11. None.	1. If cascaded use OIS lines to supply OMS as far as possible. 2. Tee off OMS line to feed ABE. 3. For systems using common tankage. Use common lines as much as possible. 4. None for OIS, OMS, and ABE. 5. None for ACPS, APU, fuel cell, EC/LSS. 6. None.	1. Common helium source for OIS, OMS, ABE. 2. Common gaseous propellant supply for OIS, OMS, AME. 3. Use OIS residuals for OMS prepressurant or pressure. 4. Use thermal control unit in OMS H_2 tank control O_2 pressure rise with H_2 vent gas. 5. Tap of OMS engine for hot gas pressurant supply. 6. Common helium supply for ACPS, APU, fuel cell, and EC/LSS oxygen. 7. ACPS high pressure gas supply for APU fuel cell and EC/LSS tanks. 8. OIS, OMS, ABE separate. 9. ACPS, APU, FC, EC/LSS separate. 10. None. 11. Warm FC tanks with EC system heat.	1. Insulation 2. Cool OMS tanks and lines with OIS residuals. 3. Cool OMS tanks and lines with thermal conditioning unit. 4. Use fuel cell reactant to vapor cool ACPS and APU tanks. 5. No integration.	1. Common orientation device for OMS and ABE. 2. Common OIS, OMS valves and regulators to the point where OMS is teed-off. 3. Common OMS-ABE valves and regulators to point where ABE is teed-off. 4. Common ACPS, APU, FC, EC/LSS valves to point of separate usage. 5. Common ACPS, APU, FC, EC/LSS acquisition system. 6. Separate OIS, OMS, ABE control. 7. Separate ACPS, APU, FC, EC/LSS control. 8. No integration.	1. Boost pump for OMS and ABE propellant supply. 2. Common pump for high pressure ACPS, APU, EC/LSS. 3. Common pump for high pressure ACPS and APU. 4. Common heat exchanger for ACPS, APU, FC, EC/LSS. 5. Common heat exchanger for ACPS, APU. 6. Common accumulators for ACPS, APU, FC, EC/LSS. 7. Use environmental control heat for fuel cell reactant heating. 8. Use EC heat for ACPS propellant heating. 9. Use EC heat for LSS oxygen heating. 10. Separate OIS, OMS and ABE fluid conditioning. 11. Separate ACPS, APU, FC, EC/LSS fluid conditioning. 12. No integration.

Table 10.2-1

APPROACH TO COMPOSITION OF INTEGRATED SYSTEM CANDIDATES (Cont)

Case	MAJOR SUBSYSTEM ELEMENTS					
	Storage	Lines	Tank Pressure Control	Thermal Control	Fluid Control	Fluid Conditioning
25	Separate OIS. Integrated OMS, Fuel Cell and EC/LSS Oxygen. Integrate ACPS, ABE, and APU.					
	1. Separate OIS. 2. Store FC and EC/LSS cryogens in OMS tanks and feed from OMS tanks. 3. Transfer FC reactant from OMS to FC tanks intermittently. 4. Separate OMS. Store EC/LSS oxygen in FC tanks. 5. Separate OMS, FC, and EC/LSS storage. 6. Separate ABE, Store ACPS and APU propellants in same tanks. 7. Store ABE, ACPS, APU in common tanks. 8. Transfer from ACPS tanks to APU tanks after first APU use. 9. Separate ACPS, ABE and APU storage. 10. All systems separate storage.	1. Separate OIS. 2. Tap off OMS lines to feed FC. 3. Tap off OMS oxygen line to feed EC/LSS. 4. Separate OMS, FC, and EC/LSS lines. 5. Use common ACPS and ABE lines where feasible. Separate APU lines. 6. Tap off ACPS lines to supply APU. 7. Separate ACPS, ABE, and APU lines. 8. All systems separate.	1. Separate OIS. 2. Common helium supply for OMS, FC, and EC/LSS. 3. Common gas supply for OMS, FC, and EC/LSS. 4. Common gas supply for FC, and EC/LSS. Tap off engine for OMS pressure. 5. Common helium supply for ACPS, ABE, and APU. 6. Common gas supply for ACPS, ABE, and APU. 7. Use ACPS accumulator gas to supply ABE and APU pressure. 8. Use TCU in OMS tanks. 9. Use TCU in ABE tanks. 10. Separate OMS, fuel cell, EC/LSS pressure systems. 11. Separate ACPS, ABE, APU systems. 12. No integration.	1. Separate OIS. 2. Circulate fluid and chill OMS lines by withdrawing FC reactant from them. 3. Vapor cool OMS tanks with FC reactants. 4. Vapor cool ABE tanks with ACPS propellants. 5. Insulation. 6. No interaction between OMS, FC, EC/LSS. 7. No interaction between ACPS, ABE, and APU. 8. No integration.	1. Separate OIS. 2. Use OMS circulation valves to control FC. 3. Tap of FC supply lines and valves to feed EC/LSS. 4. Use common orientation device in OMS tank for OMS, FC, and EC/LSS propellants. 5. Separate OMS, FC, and EC/LSS systems. 6. Separate ACPS, ABE, and APU. 7. No integration.	1. Separate OIS. 2. Use OMS pumps to resupply FC and EC/LSS. 3. Use ACPS pumps to supply ABE. 4. Use EC heat to warm FC reactants. 5. Use ACPS heat exchangers to heat APU propellant. 6. No integration between OMS, FC, and EC/LSS. 7. No integration between ACPS, ABE, and APU. 8. No integration.
26	Integrate OIS, OMS, ACPS. Integrate ABE, APU, Fuel Cell, EC/LSS.					
	1. Cascade OIS propellant through OMS tanks. Store ACPS propellants in OMS tanks. 2. Separate OIS. 3. Store ACPS propellant in OMS tanks. 4. Resupply ACPS from OMS tanks. 5. Store ABE, APU, FC, EC/LSS in common tanks. 6. Separate ABE storage. 7. Common APU, FC, EC/LSS storage. 8. No OIS, OMS, ACPS integration. 9. No ABE, APU, FC, EC/LSS integration. 10. No integration. 11. Use OIS residuals for ACPS propellant. 12. Refill ACPS tanks from OMS high pressure pump.	1. Use OIS lines for OMS feed where possible. 2. Use OIS lines for ACPS propellant distribution. 3. Use OIS lines for ACPS accumulators. 4. Separate OIS. 5. No OMS and ACPS integration. 6. No ABE, APU, FC, EC/LSS integration. 7. Circulate and chill propellant in OMS 8. Circulate and chill fuel in ABE lines by withdrawing FC reactant from it. 9. No integration.	1. Supply OIS, OMS, and ACPS with common helium pressurization. 2. Separate OIS supply gas or helium. 3. Common gas supply for OMS and ACPS. 4. No OIS, OMS, ACPS integration. 5. Use ACPS gas from accumulators to supply OMS. 6. Separate ABE pressurant supply. 7. Use common helium supply for APU, FC, and EC/LSS. 8. Use common gas supply for APU, FC, and EC/LSS. 9. Use TCU in OMS tank. 10. Use TCU in ACPS. 11. No ABE, APU, FC, EC/LSS integration. 12. No integration.	1. Vapor cool OMS lines and tanks with OIS residuals. 2. Vapor cool OMS lines and tanks with ACPS propellant as it is withdrawn. 3. Circulate and chill OMS lines by withdrawing ACPS propellant from them. 4. Place ACPS tanks inside OMS tanks. 5. No OIS, OMS, ACPS integration. 6. Vapor cool ABE lines and tank with FC. 7. Store FC hydrogen in ABE hydrogen tank. 8. No ABE, APU, FC, EC/LSS integration.	1. Use common OIS and OMS valves if tanks are cascaded. 2. Use common orientation device for OMS and ACPS. 3. Separate OIS. 4. No OIS, OMS, ACPS integration. 5. Separate ABE. 6. Use common values and regulators for APU, FC, EC/LSS where 7. No ABE, APU, FC, 8. No integration.	1. Separate OIS. 2. Use common pump for OMS and ACPS. 3. Use common heat exchangers for OMS and ACPS. 4. Use OIS tanks as thermal conditioners and as accumulators for ACPS. 5. OMS pumps for high pressure 6. No OIS, OMS, ACPS integration. 7. Use common pump for APU and FC reactants. 8. Use common heat exchangers for APU and FC reactants. 9. Heat APU and FC from EC heat. 10. Separate ABE. 11. No ABE, APU, FC, and EC/LSS integration. 12. No integration.

Table 10.2-1

APPROACH TO COMPOSITION OF INTEGRATED SYSTEM CANDIDATES (Cont)

Case	MAJOR SUBSYSTEM ELEMENTS					
	Storage	Lines	Tank Pressure Control	Thermal Control	Fluid Control	Fluid Conditioning
27	Integrated OIS, OMS. Integrated ACPS, ABE Fuel, APU, Fuel Cell, and EC/LSS					
	1. Cascade OIS and OMS tanks. 2. No OIS and OMS integration. 3. Store ACPS, APU, FC, ABE, and EC/LSS in common tanks. 4. ABE separate. 5. Store ACPS, APU, FC and EC/LSS in common tanks. 6. Resupply APU tanks from ACPS tanks. 7. Store ACPS and APU propellants in common tanks. 8. Store FC and EC/LSS cryogens in common tanks. 9. Resupply FC tanks from ACPS tanks. 10. No ACPS, ABE, APU, FC, or EC/LSS integration. 11. No integration. 12. Store ABE and APU in common tanks. 13. Store ACPS, FC, and EC/LSS in common tanks.	1. Use same lines for OIS and OMS if cascaded. 2. No OIS or OMS integration. 3. When common storage is used use common lines as much as possible. 4. No ACPS, ABE, APU, FC, or EC/LSS integration. 5. No integration.	1. Common pressurization for OIS and OMS if cascaded. 2. Use OIS residuals to pressurize OMS. 3. Separate pressurant. Supply for OIS and OMS. 4. Common helium supply for ACPS, ABE, APU, FC, EC/LSS. 5. Store helium supply in ACPS hydrogen tank. 6. Store helium supply in ABE hydrogen tank. 7. Use ACPS accumulator gas to supply ABE, APU, and FC. 8. Use TCU in OMS tank. 9. Use TCU in ACPS tanks. 10. Use TCU in ABE tanks. 11. Use FC heat to maintain pressure in one or all of ACPS, APU, FC, and EC/LSS in stored supercritically.	1. Cool OMS lines and tanks with OIS residuals. 2. No OMS-OIS integration. 3. Cool ABE line and tank with ACPS propellant as it is withdrawn. 4. Cool any or all of ACPS, APU, FC, or EC/LSS lines and tanks with vapor from ABE TCU vent. 5. Cool APU tanks and lines with ACPS or FC hydrogen as it is used. 6. Store APU hydrogen tank inside APU tank cool APU O_2 tank with ABE hydrogen. 7. Store APU tanks inside ACPS.	1. If OIS and OMS are cascaded. Use same valves and regulators as much as possible. 2. No OIS-OMS integration. 3. Where common tankage is used for ACPS, ABE, APU, FC, or EC/LSS use common valves and regulators where possible. 4. No ACPS, ABE, APU; FC, or EC/LSS integration. 5. No integration.	1. No OIS, OMS integration. 2. Use common pump system for ACPS, ABE, APU, FC, and EC/LSS. 3. Same as 2 except separate pump for ABE. 4. Use common heat exchanger system and warm gas storage accumulators for ACPS, APU, FC, and EC/LSS. 5. Use FC heat to thermally condition all or some of ACPS, APU, FC, and EC/LSS. 6. No ACPS, ABE, FC, APU, FC, and EC/LSS integration. 7. No integration.
28	Separate OIS. Integrate OMS, ACPS, ABE Fuel, APU, Fuel Cells, and EC/LSS Oxygen.					
	1. Separate OIS. 2. Store OMS, ACPS, ABE, APU, FC, and EC/LSS cryogens in common tanks. 3. Store OMS and ABE propellant in common tanks. 4. Store ACPS, APU, FC, and EC/LSS cryogens in common tanks. 5. Store ABE propellant separate. 6. Store OMS propellant separate. 7. Store ACPS, APU, FC in common tanks.	1. Where common storage is used, use common lines as much as possible.	1. Separate OIS. 2. Common helium supply for OMS, ACPS, ABE, APU, FC, and EC/LSS, store in OMS tank. 3. Separate helium supply for ABE. Store in ABE fuel tank. 4. If supercritical storage, maintain ACPS, APU, FC, and EC/LSS pressure with FC heat. 5. Pressurize any or all of OMS, ACPS, APU, FC, and/or EC/LSS with gas from conditioned storage accumulators.	1. Separate OIS. 2. Vapor coolOMS tank and lines with FC reactants as it is withdrawn. 3. Vapor cool ACPS tank and lines with FC reactants as it is withdrawn. 4. Vapor cool OMS tanks and lines with ACPS propellants as they are used. 5. Store FC reactant in OMS tanks.	1. Where common lines are used use common valves and regulators as much as possible. 2. Use common orientation devices where common storage is used.	1. Separate OIS. 2. Use common pumps for OMS, ACPS, APU. 3. Separate ABE pumps. 4. Use common pumps for OMS, ACPS, ABE, APU, FC, and EC/LSS. 5. Use common heat exchanger system for ACPS, APU, FC, EC/LSS. 6. Use common accumulator storage system for applicable subsystems.

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Table 10.2-1

APPROACH TO COMPOSITION OF INTEGRATED SYSTEM CANDIDATES (Cont)

Case	MAJOR SUBSYSTEM ELEMENTS					
	Storage	Lines	Tank Pressure Control	Thermal Control	Fluid Control	Fluid Conditioning
	8. Store EC/LSS separate. 9. Resupply APU from OMS tanks. 10. Resupply ACPS, APU, FC from OMS. 11. No ACPS, APU, ABE, FC, or EC/LSS integration. 12. Use OMS vapor for FC and EC/LSS.			6. Use TCU in ABE tank - cool OMS tanks and lines with vented vapor. 7. Use TCU in OMS - cool any or all of other systems with vented vapor.		
29	Integrates All Systems.					
	1. Separate OIS. 2. Cascade OIS and OMS. 3. Store all cryogens in OMS tanks except OIS. 4. Resupply from OIS tanks to APU during ascent. 5. Use OIS residuals and vapor to feed APCS and/or FC. 6. Store OMS, ABE, and ACPS propellant in common tanks. 7. Store APU, FC, and EC/LSS in common tanks. 8. Resupply ACPS and APU from OMS tanks. 9. Supply FC and EC/LSS from OMS vapor.	1. Where common storage is used, use common lines as much as possible. 2. Use OIS lines for ACPS distribution or storage accumulators.	1. Separate OIS. 2. Common helium supply for all systems other than OIS. Store in OMS propellant tanks. 3. Use common gas supply from conditioned accumulators. 4. Use engine bleed for OMS and ABE if available. 5. Use TCU in OMS tank. 6. Use TCU in ABE tank. 7. Use FC heat to maintain pressure of ACPS, APU, FC and EC/LSS tanks if they are supercritical.	1. Use OIS residuals and vapors to cool any one or more of the other system tanks and lines. 2. Place APU tank in ABE tank. Thermally connect APU O_2 tank to ABE tank. 3. Place APU tanks in OMS tanks. 4. Place FC tanks inside OMS tanks. 5. Withdraw FC reactants from OMS lines to circulate and cool OMS lines.	1. Where common lines are used, use as many common valves and regulators as possible. 2. Use OIS lines for ACPS distribution.	1. Use OIS lines and tanks as accumulators and thermal conditioners for ACPS and/or FC. 2. Use common pump for supply of all systems except OIS and ABE. 3. Use common heat exchangers for ACPS, APU, FC, and EC/LSS. 4. Use OMS engine for heating OMS propellant. 5. Use ABE engine for heating ABE fuel. 6. Use FC heat to condition ACPS, FC, APU and EC/LSS cryogens.
30	Integrate OIS and OMS. Integrate ACPS and APU. Integrate ABE and Fuel Cell Fuel. Integrated Fuel Cell and EC/LSS Oxygen.					
	1. Cascade OIS and OMS. 2. Store APU propellant in ACPS tanks. 3. Resupply APU from ACPS. 4. Store FC fuel in ABE tanks. 5. Resupply FC fuel 6. Store EC/LSS oxygen in fuel cell oxygen tank. 7. Resupply EC/LSS from fuel cell oxygen tank.	1. Where common storage is used use common lines.	1. Use engine bleed for OIS and OMS. 2. Use ACPS accumulator gas to pressurize APU. 3. Use FC heat to build up and/or maintain pressure 4. Use separate helium system for ABE.	1. Use OIS residuals and vapors to cool OMS tanks and lines. 2. Use ACPS propellant to cool APU tanks as it is withdrawn. 3. Use TCU in OMS. 4. Use TCU in ABE. Cool FC tank with TCU vapor.	1. Where common lines are used, use common valves and accumulators.	1. Use ACPS pumps for APU propellant. 2. Use ACPS heat exchangers for APU thermally conditioning. 3. Use FC heat to condition FC and EC/LSS propellants in tanks and lines.

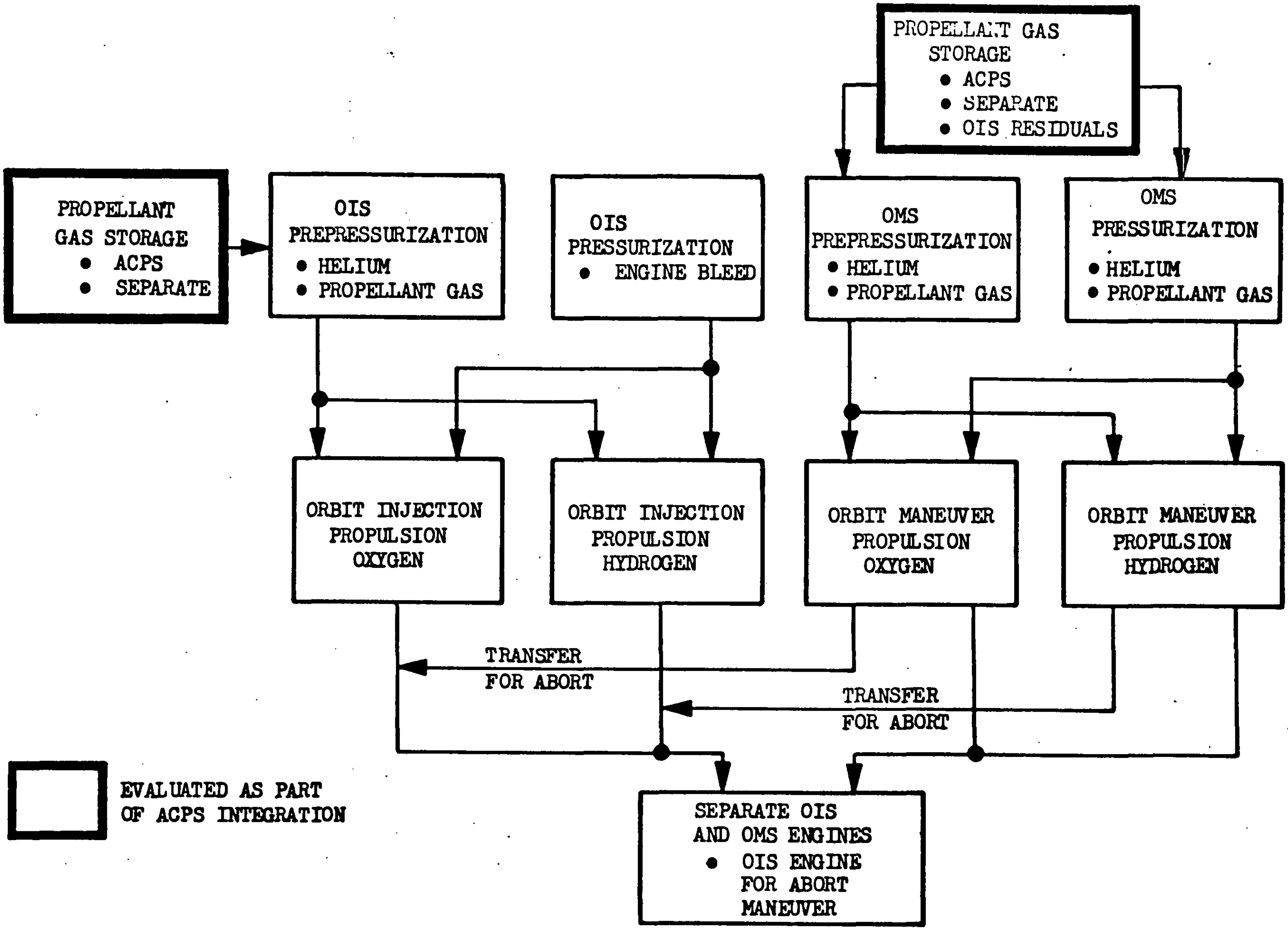

Fig. 10.2-1 Case 2: Integrate OIS and OMS

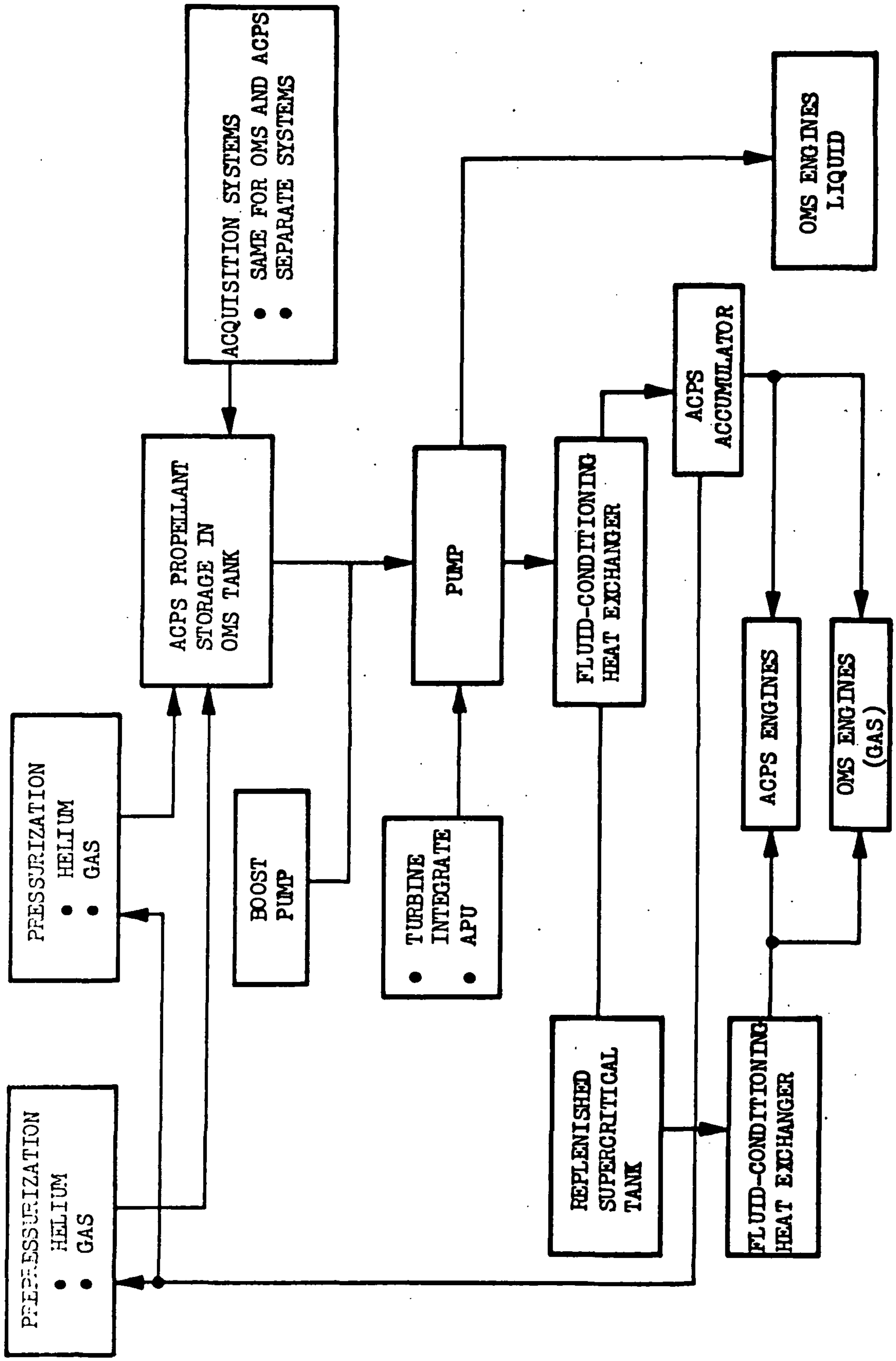

Fig. 10.2-2 Case 3: Integrate OMS and ACPS

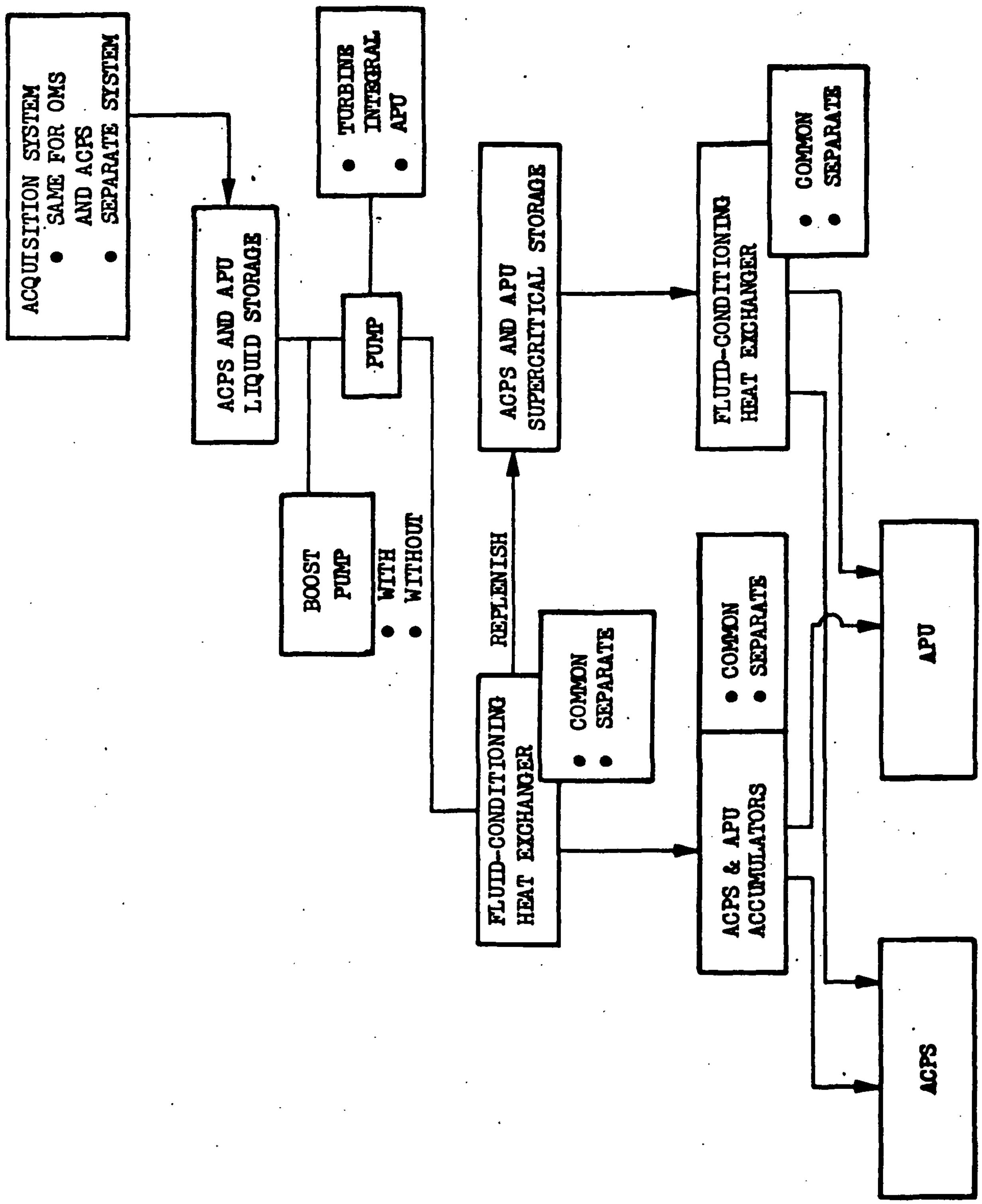

Fig. 10.2-3 Case 4: Integrate ACPS and APU

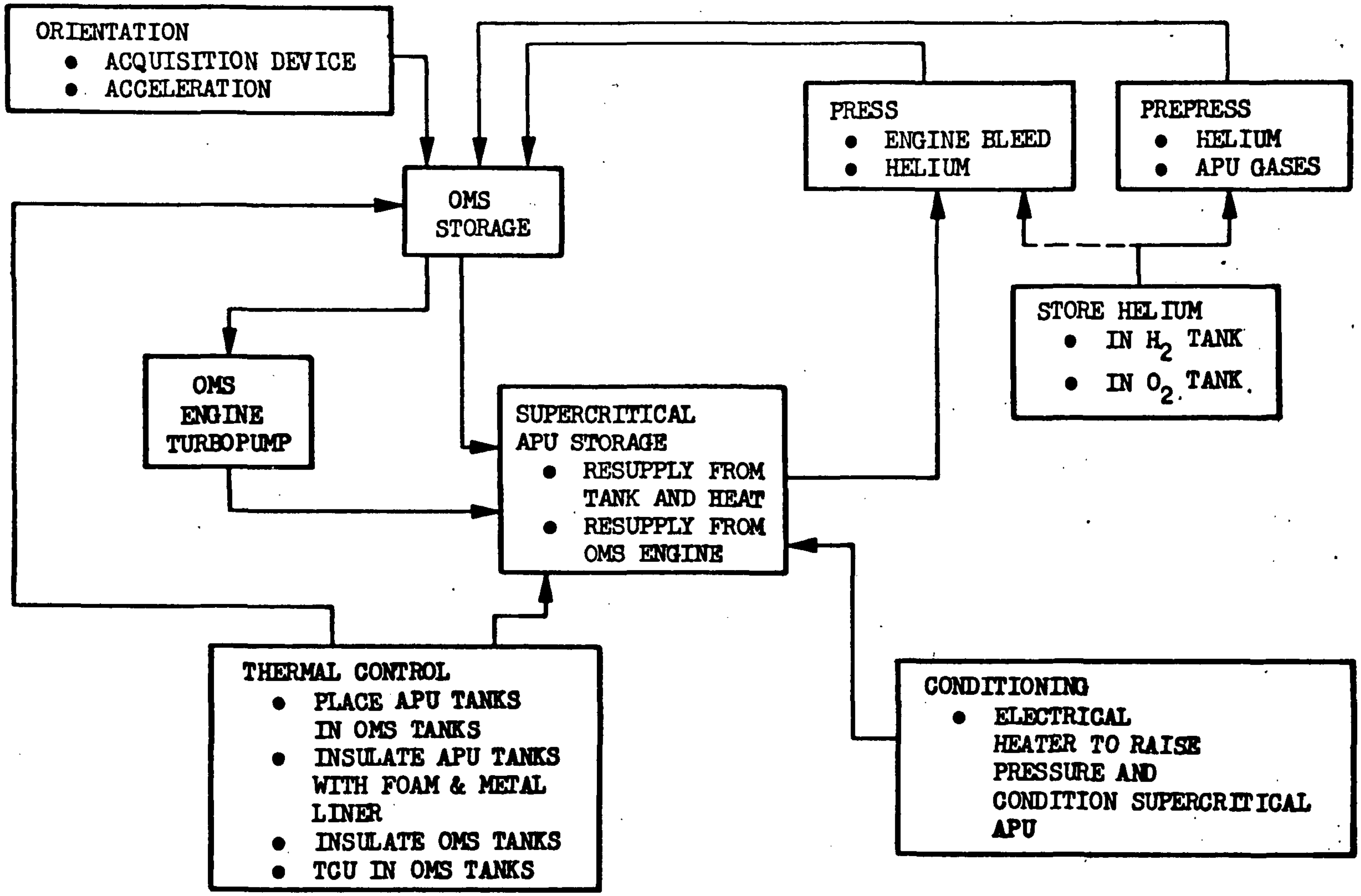

Fig. 10.2-4 Case 5: Integrate OMS and APU

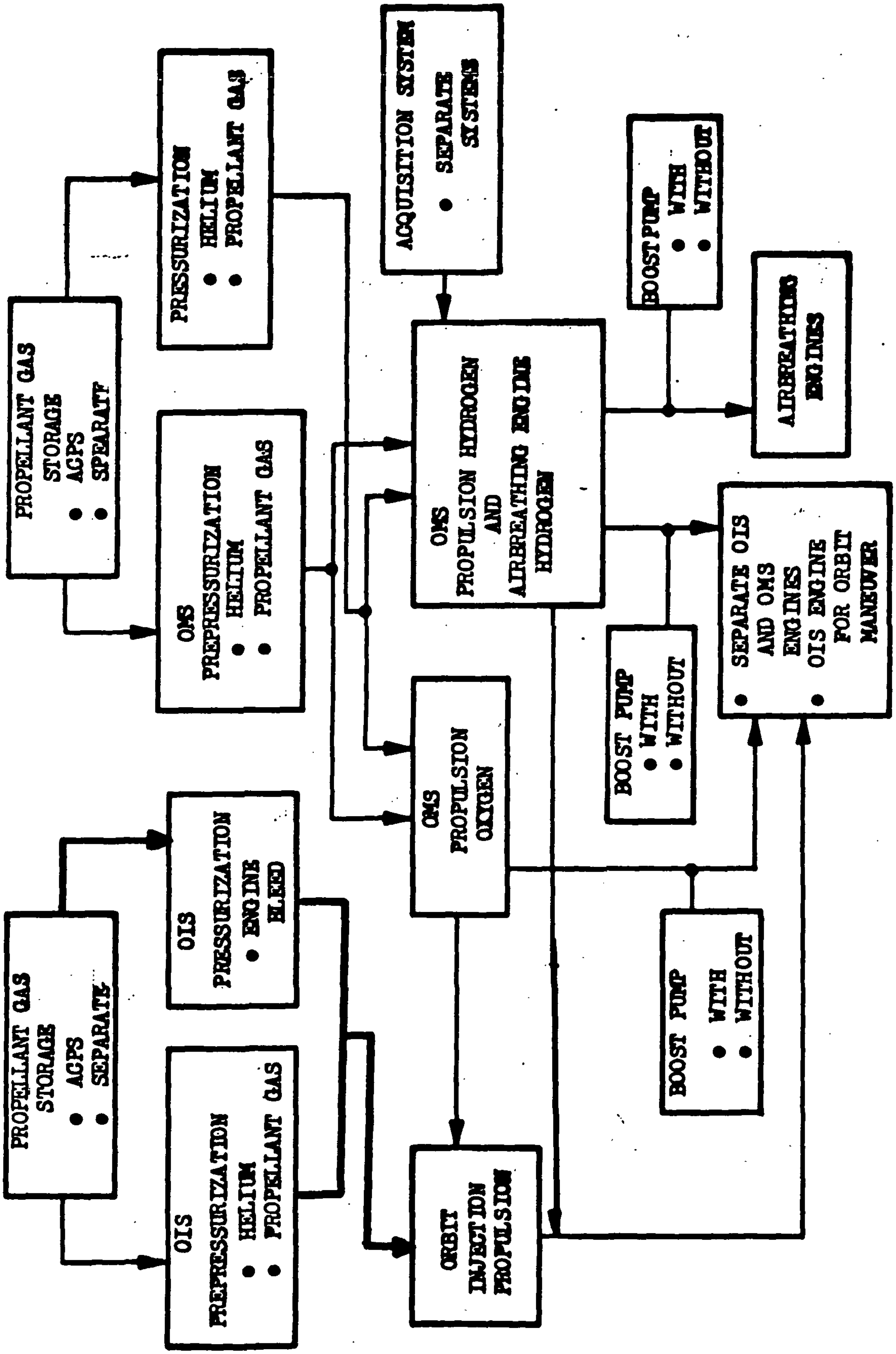

Fig. 10.2-5 Case 6: Integrate OMS and ABE Hydrogen

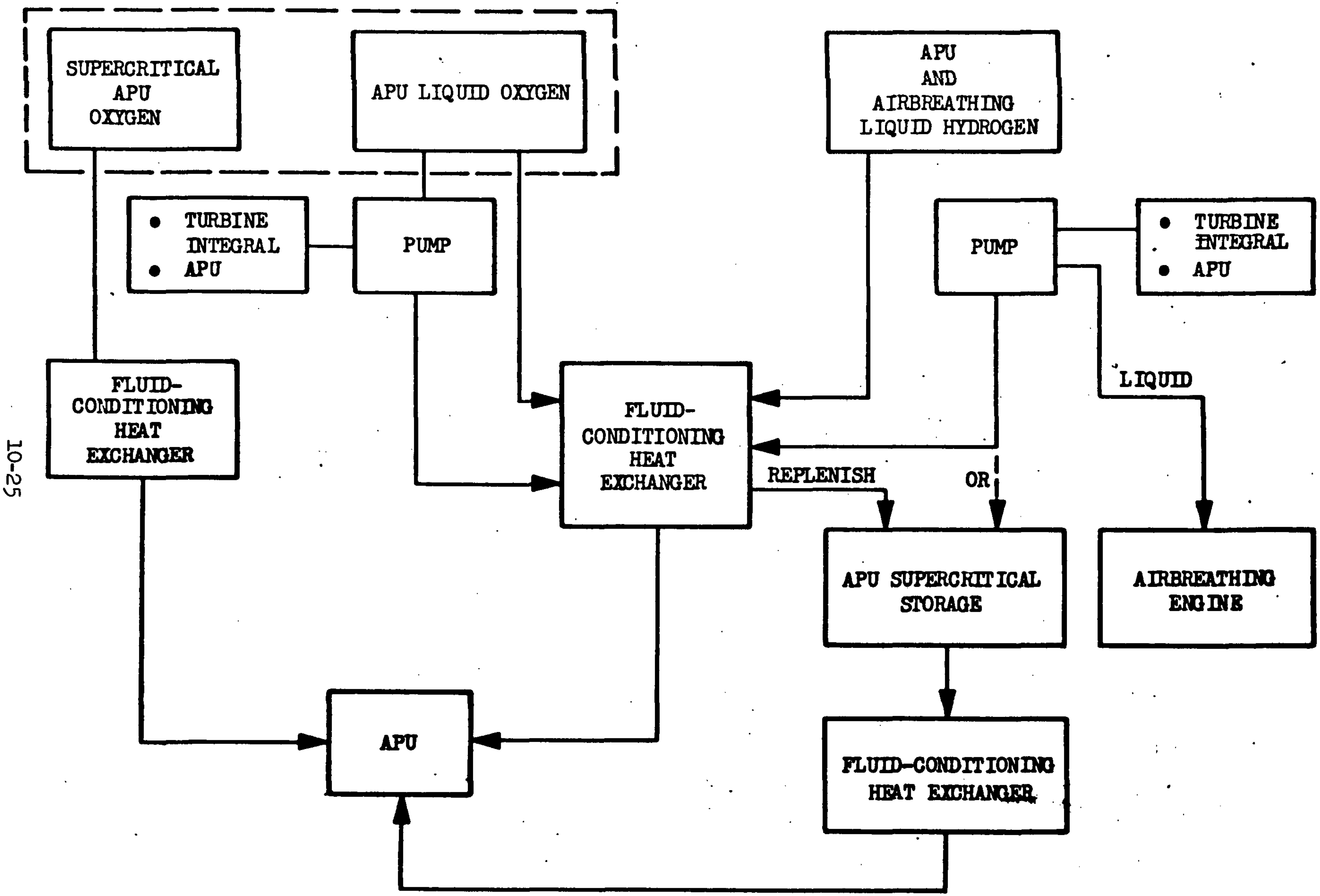

Fig. 10.2-6 Case 7: Integrate APU and ABE Systems

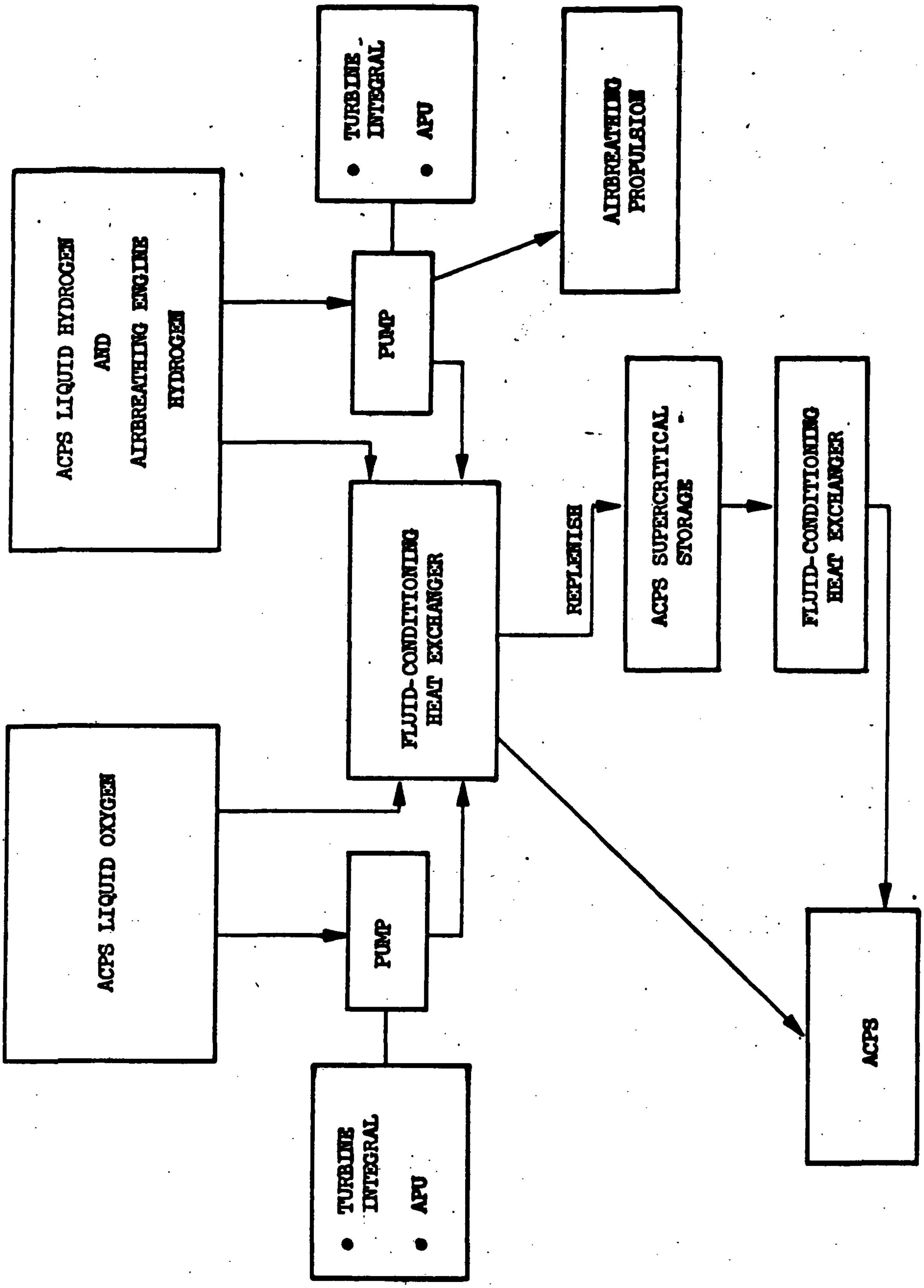

Fig. 10.2-7 Case 8: Integrate ACPS and ABE Hydrogen

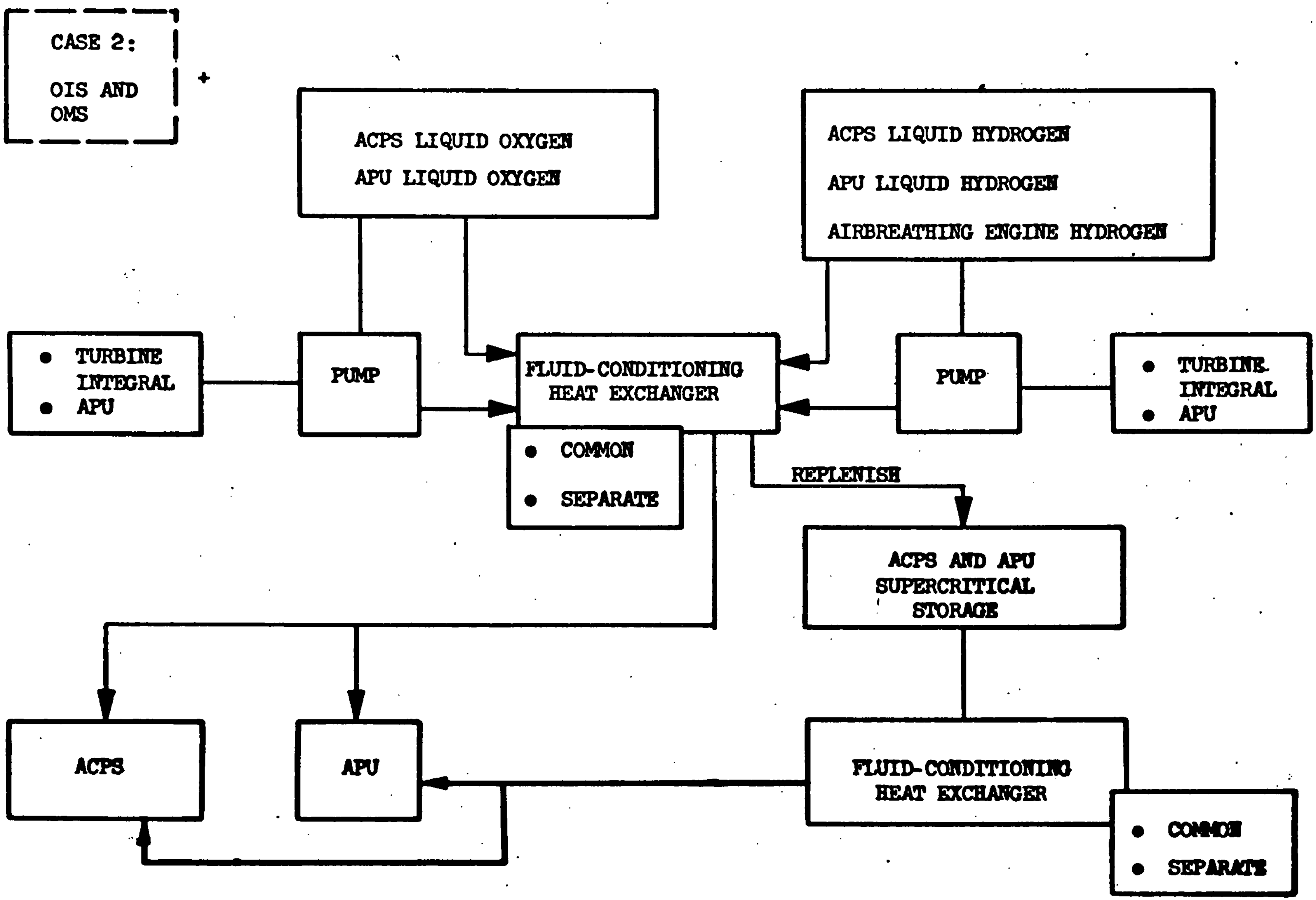

Fig. 10.2-8 Case 10: Integrate OIS and OMS; Integrate ACPS, APU, and ABE Hydrogen

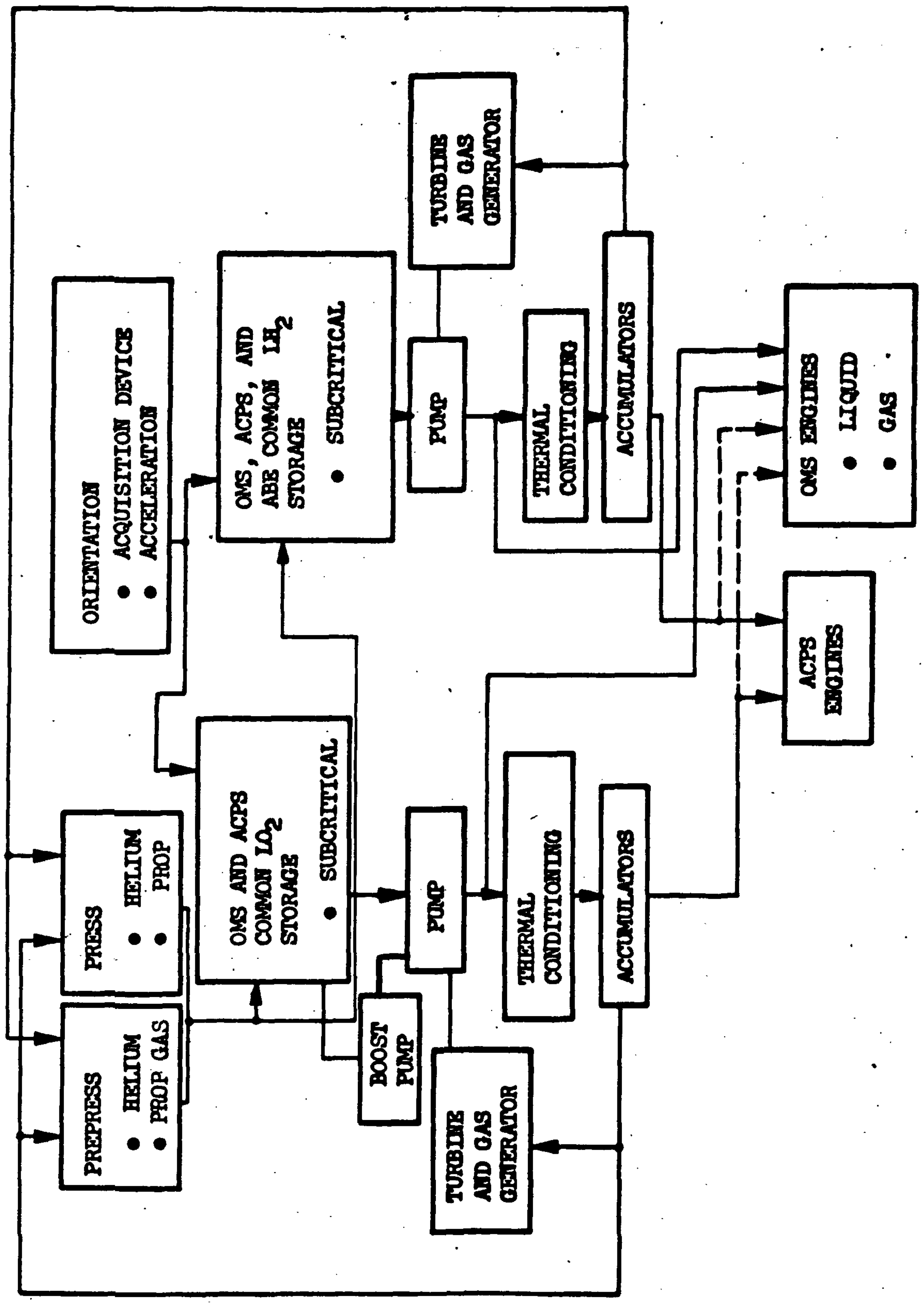

Fig. 10.2-9 Case 15: Integrate OMS, ACPS, and ABE Hydrogen

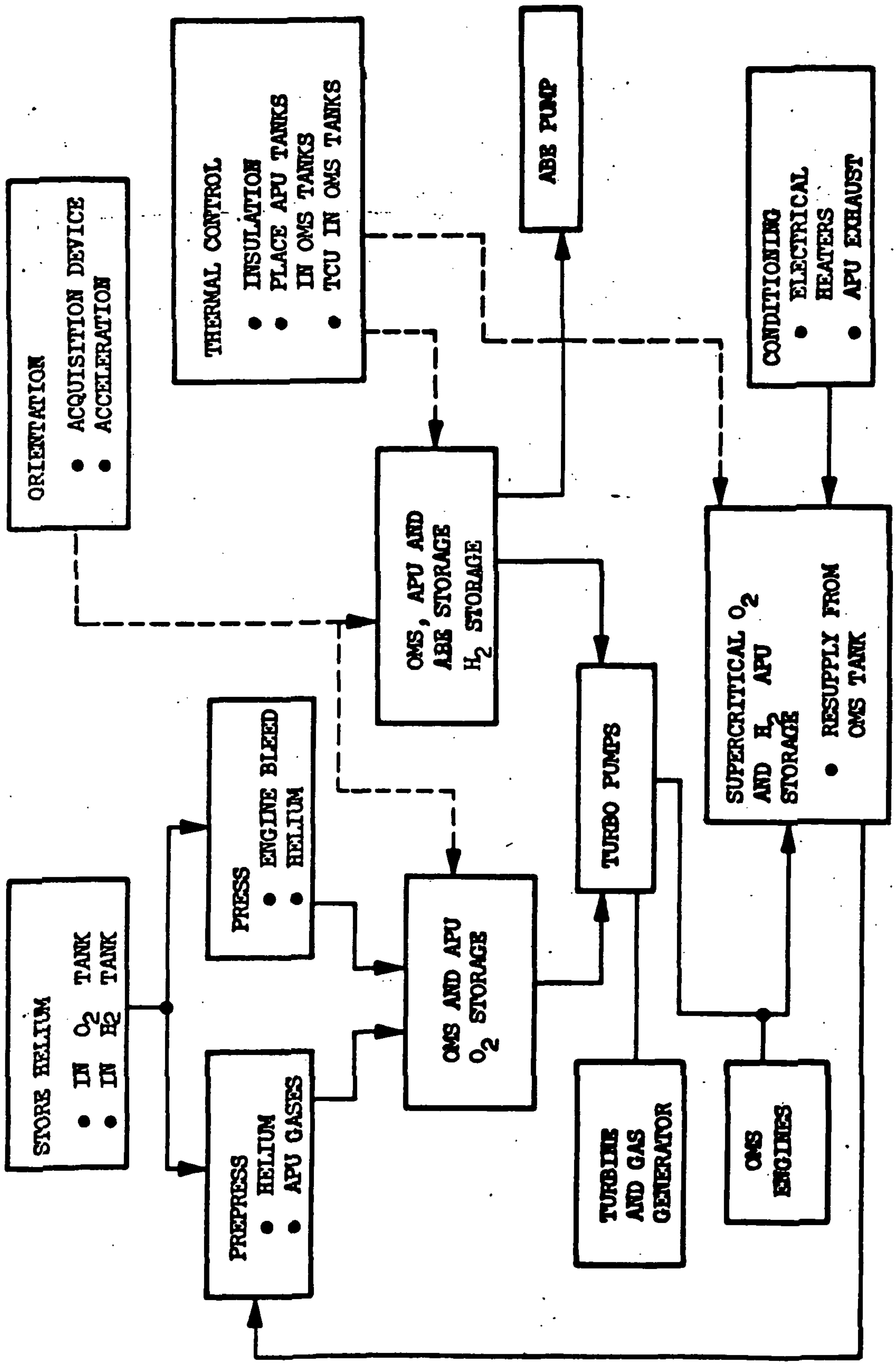

Fig. 10.2-10 Case 16: Integrate OMS, APU, and ABE Hydrogen

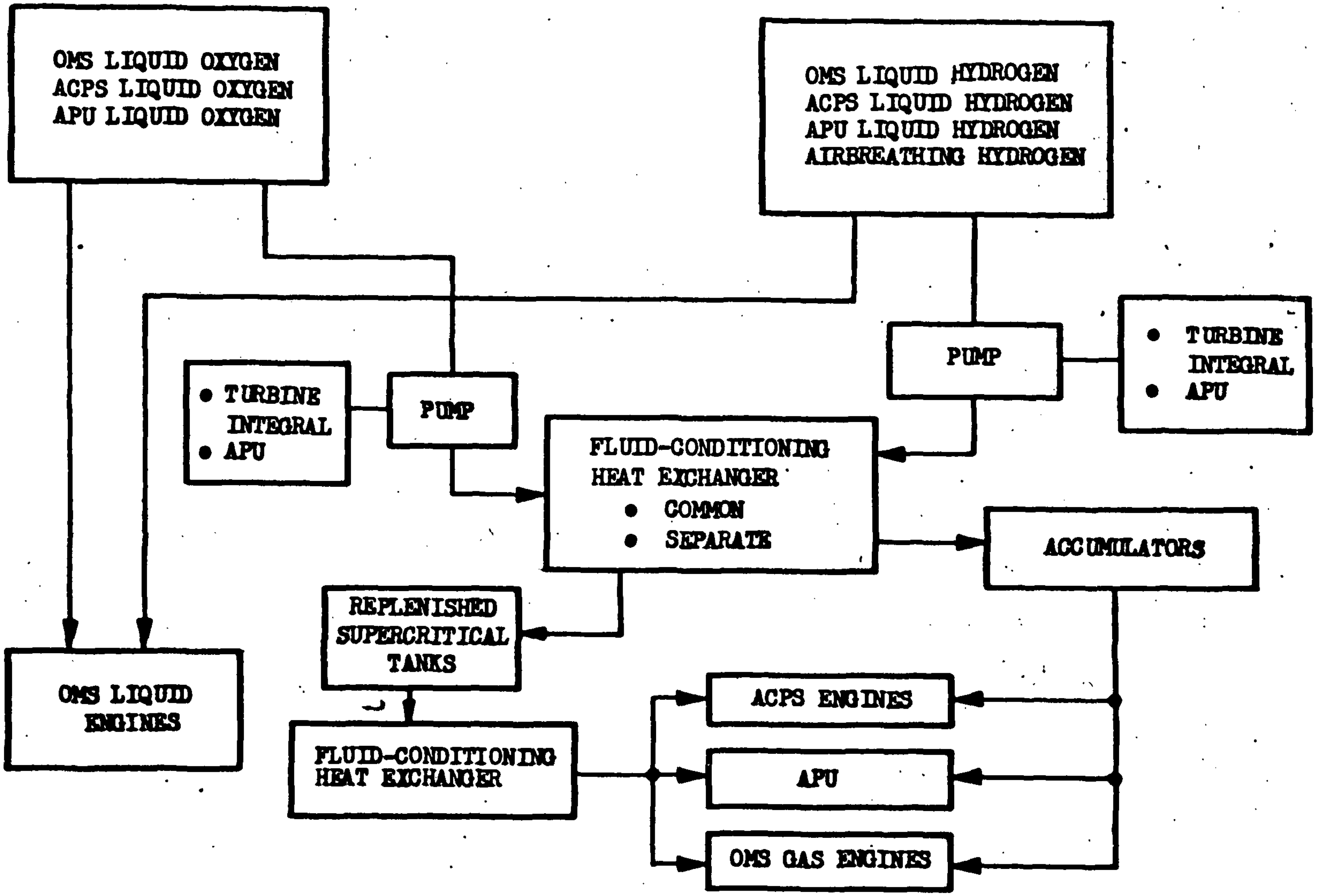

Fig. 10.2-11 Case 19: Integrate OMS, ACPS,APU System and ABE Hydrogen

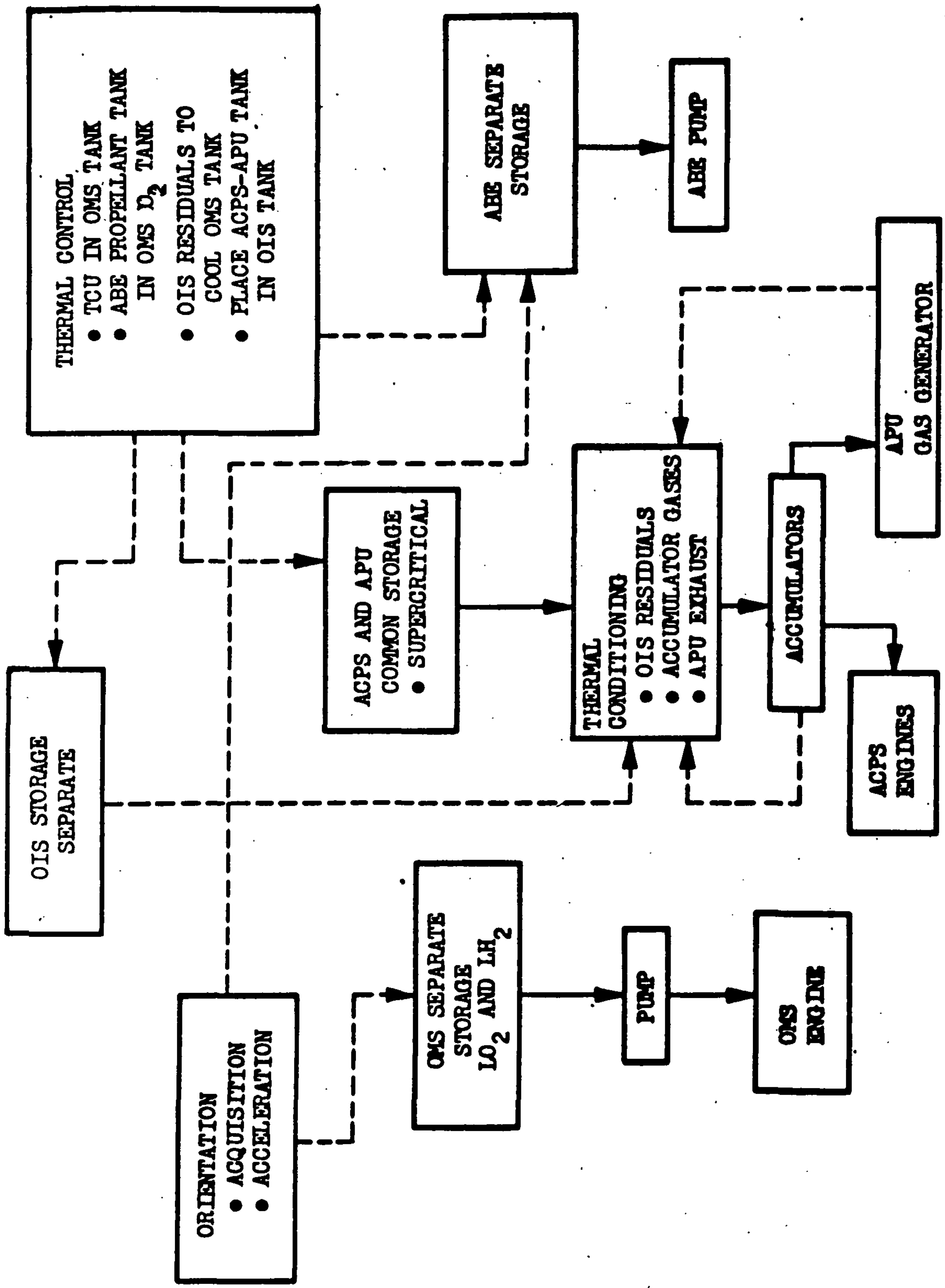

Fig. 10.2-12 Case 20: Integrate OIS, OMS, ACPS, APU System, and ABE Hydrogen

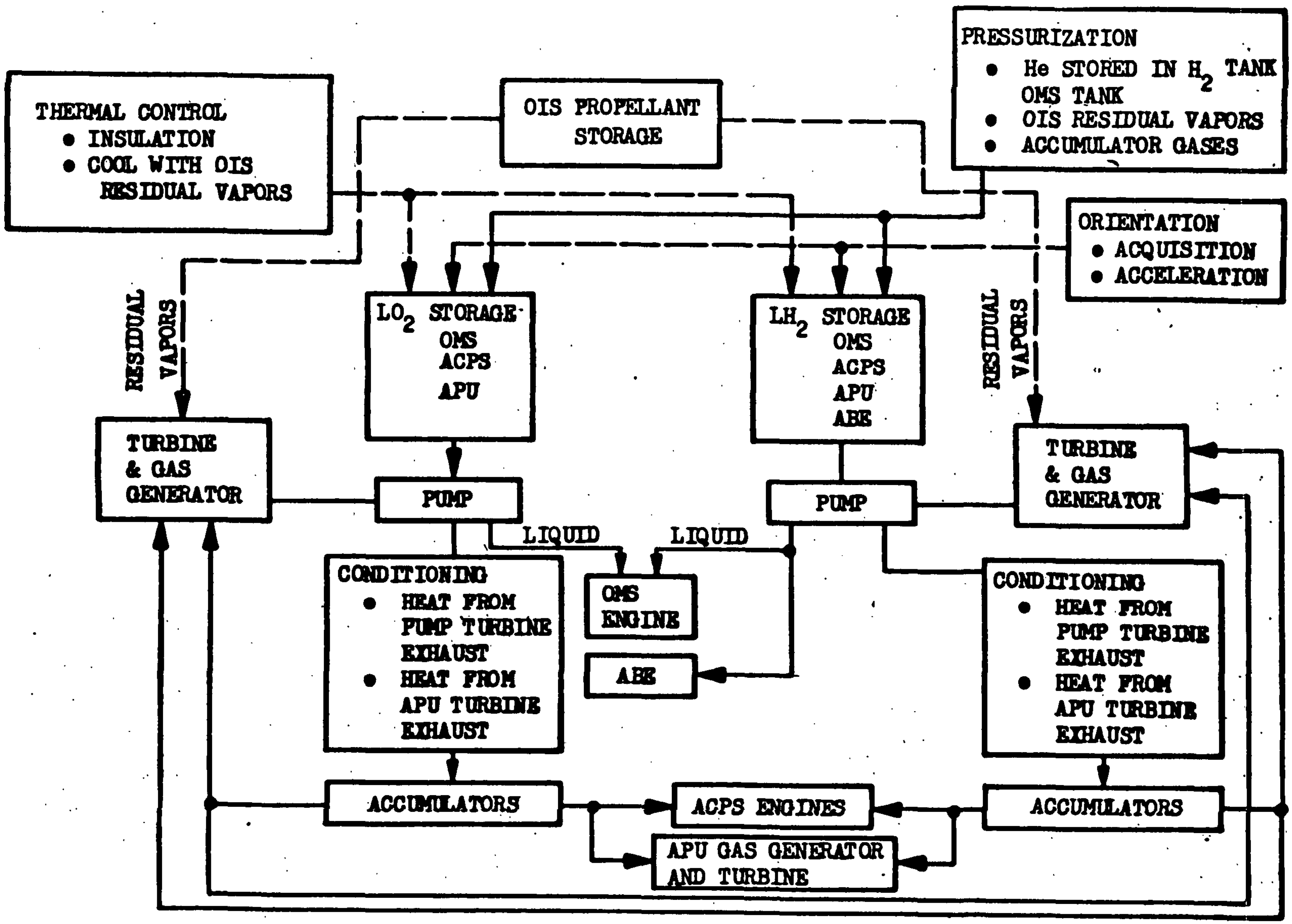

Fig. 10.2-13 Case 20(a): Integrate OIS, OMS, ACPS, APU System, and ABE Hydrogen

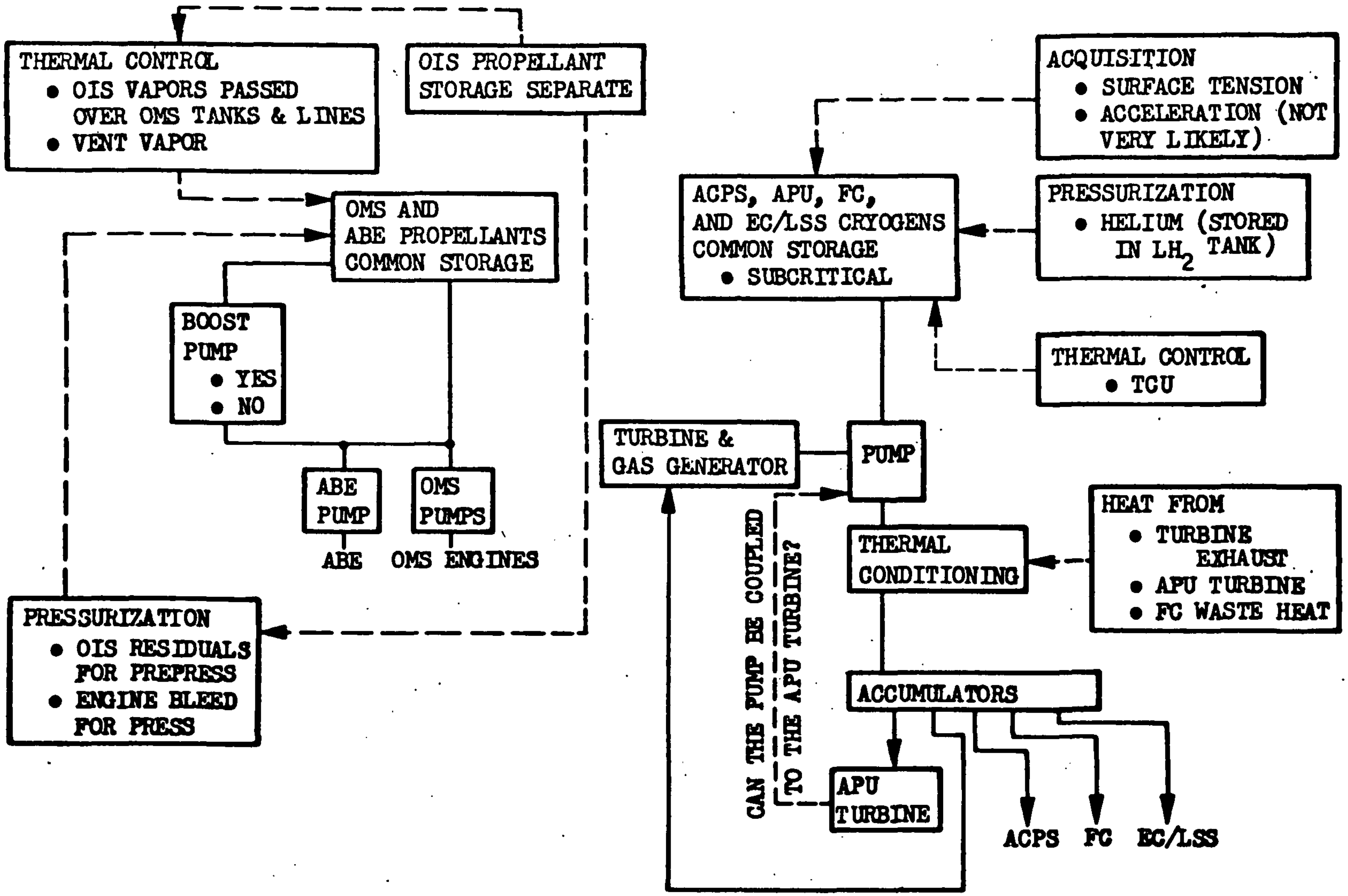

Fig. 10.2-14 Case 24: Integrate OIS, OMS, and ABE Hydrogen; Integrate ACPS, APU System, Fuel Cell System and EC/LSS Oxygen

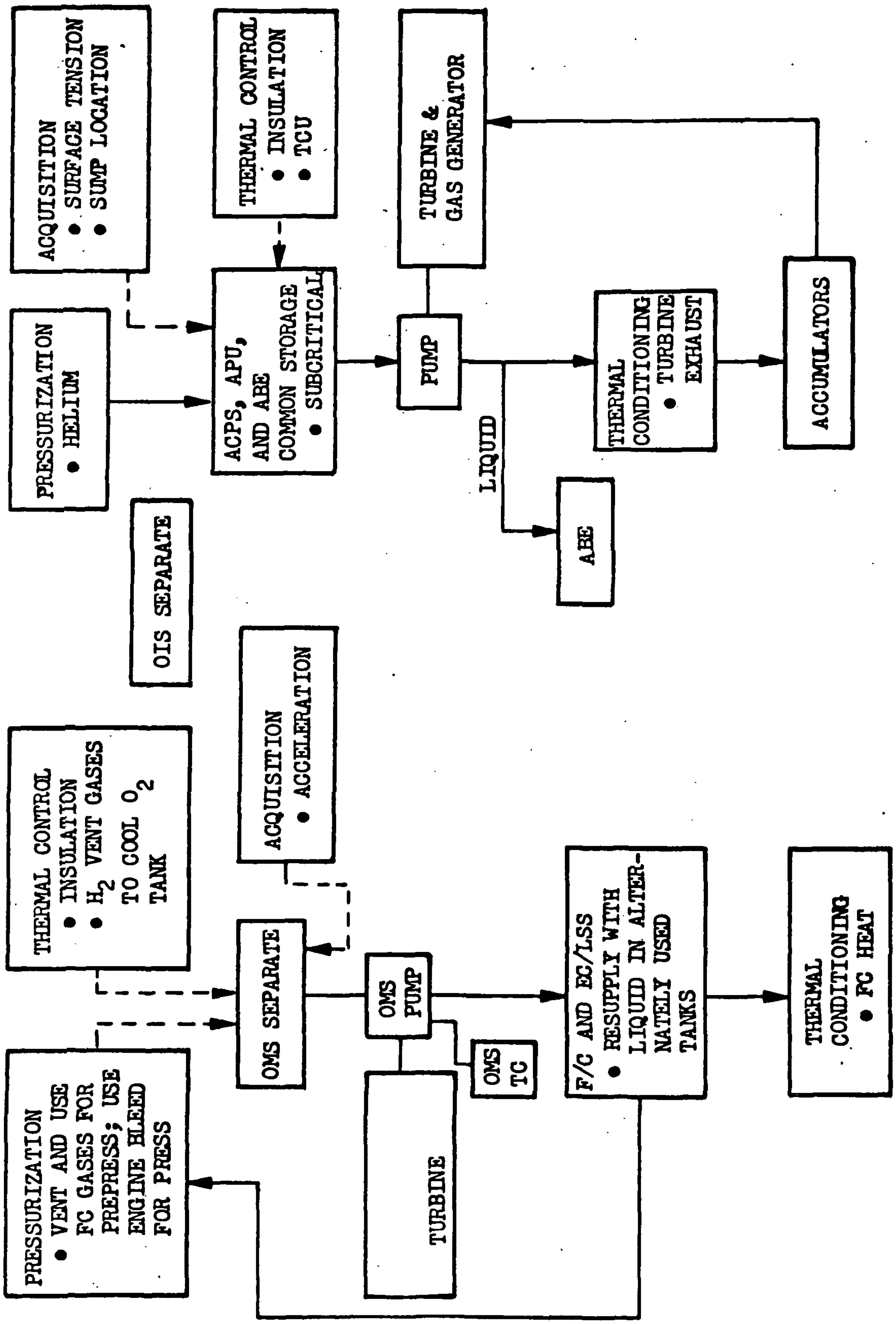

Fig. 10.2-15 Case 25: Integrate OMS, Fuel Cell System and EC/LSS Oxygen; Integrate ACPS, APU System, and ABE Hydrogen

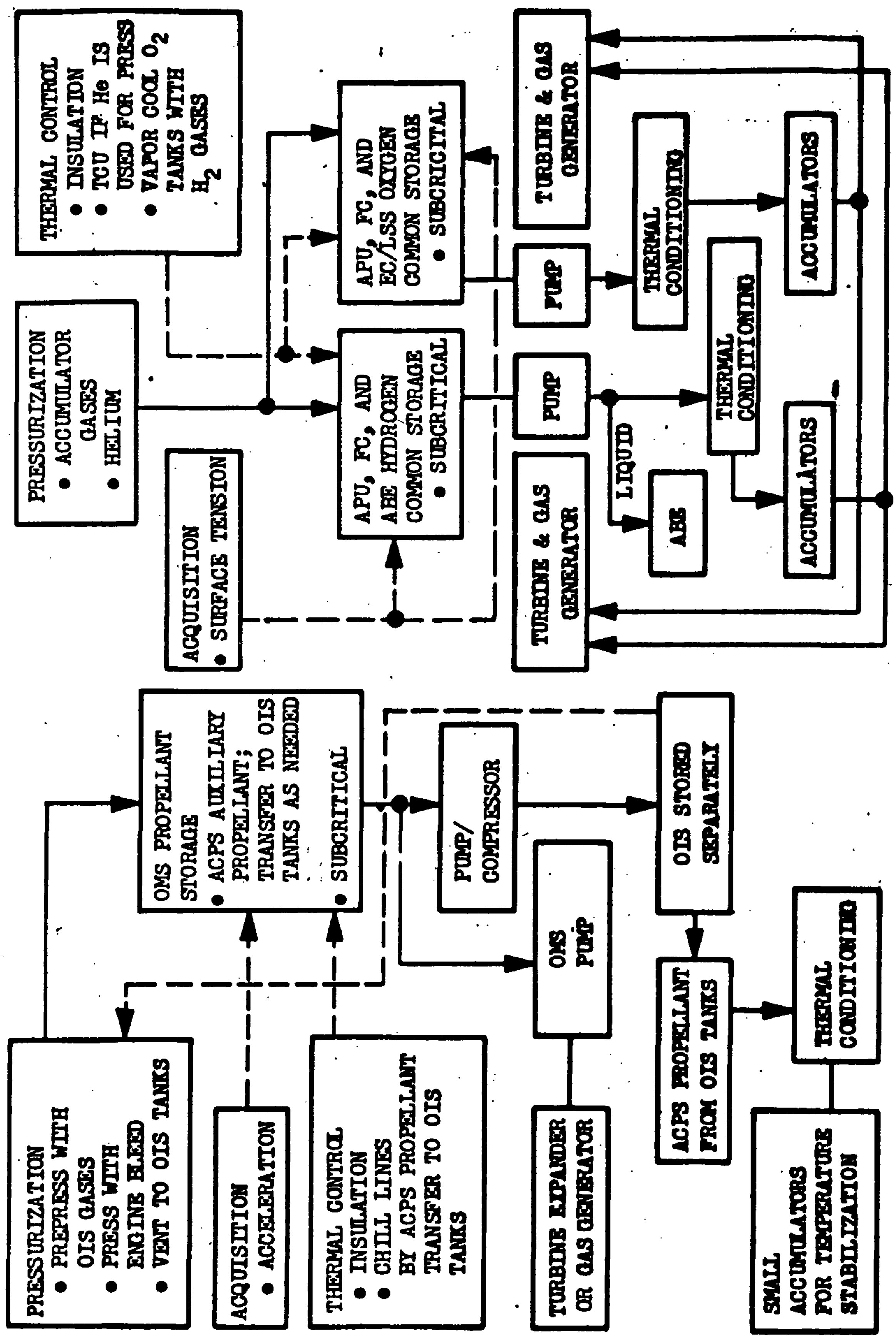

Fig. 10.2-16 Case 26: Integrate OIS, OMS, ACPS; Integrate ABE Hydrogen, APU System, Fuel Cell System and EC/LSS Oxygen

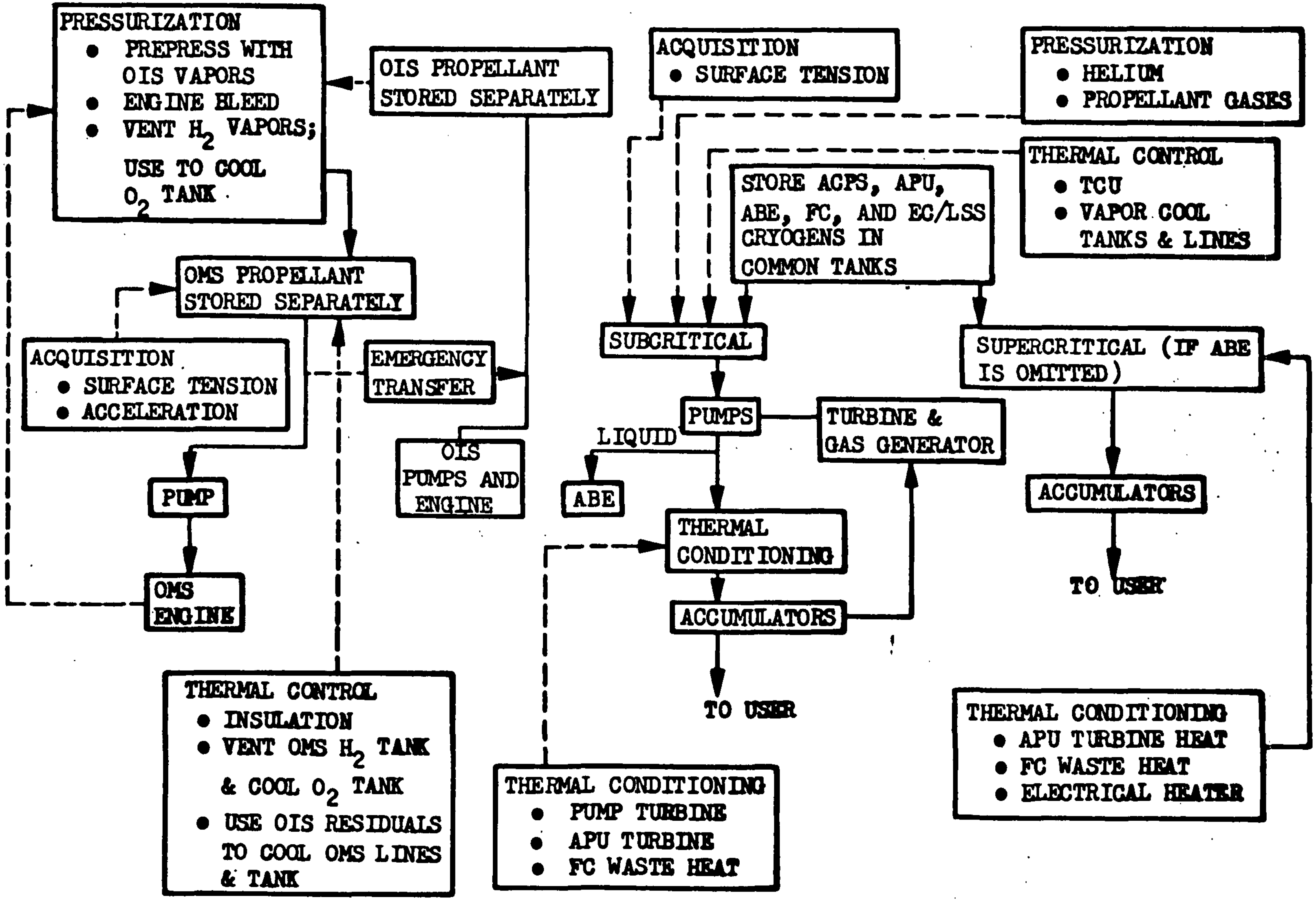

Fig. 10.2-17 Case 27: Integrate OIS, OMS; Integrate ACPS, ABE, Fuel Cell and EC/LSS

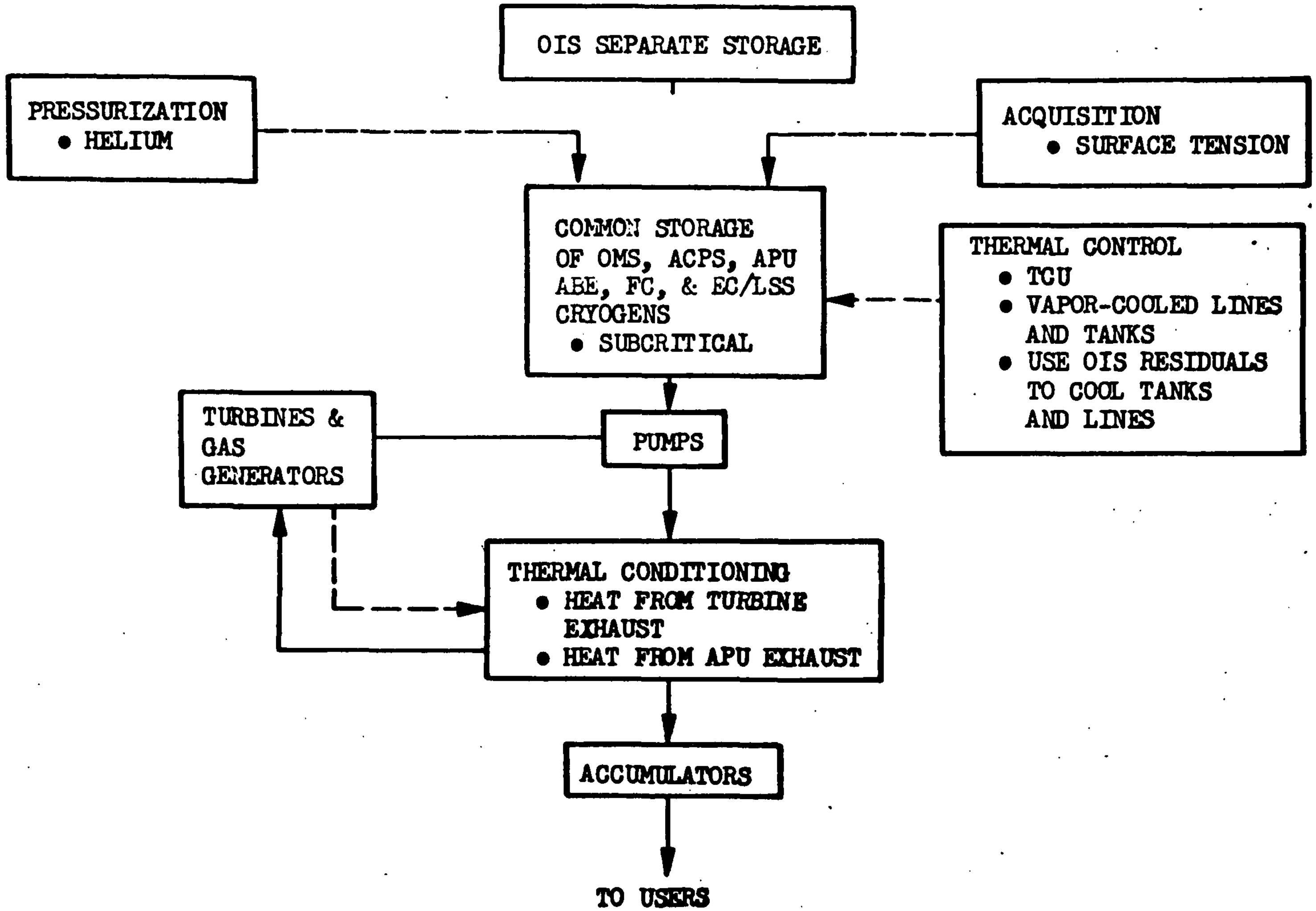

Fig. 10.2-18 Case 28: Integrate OMS, ACPS, ABE Hydrogen, APU, Fuel Cell, and EC/LSS Oxygen

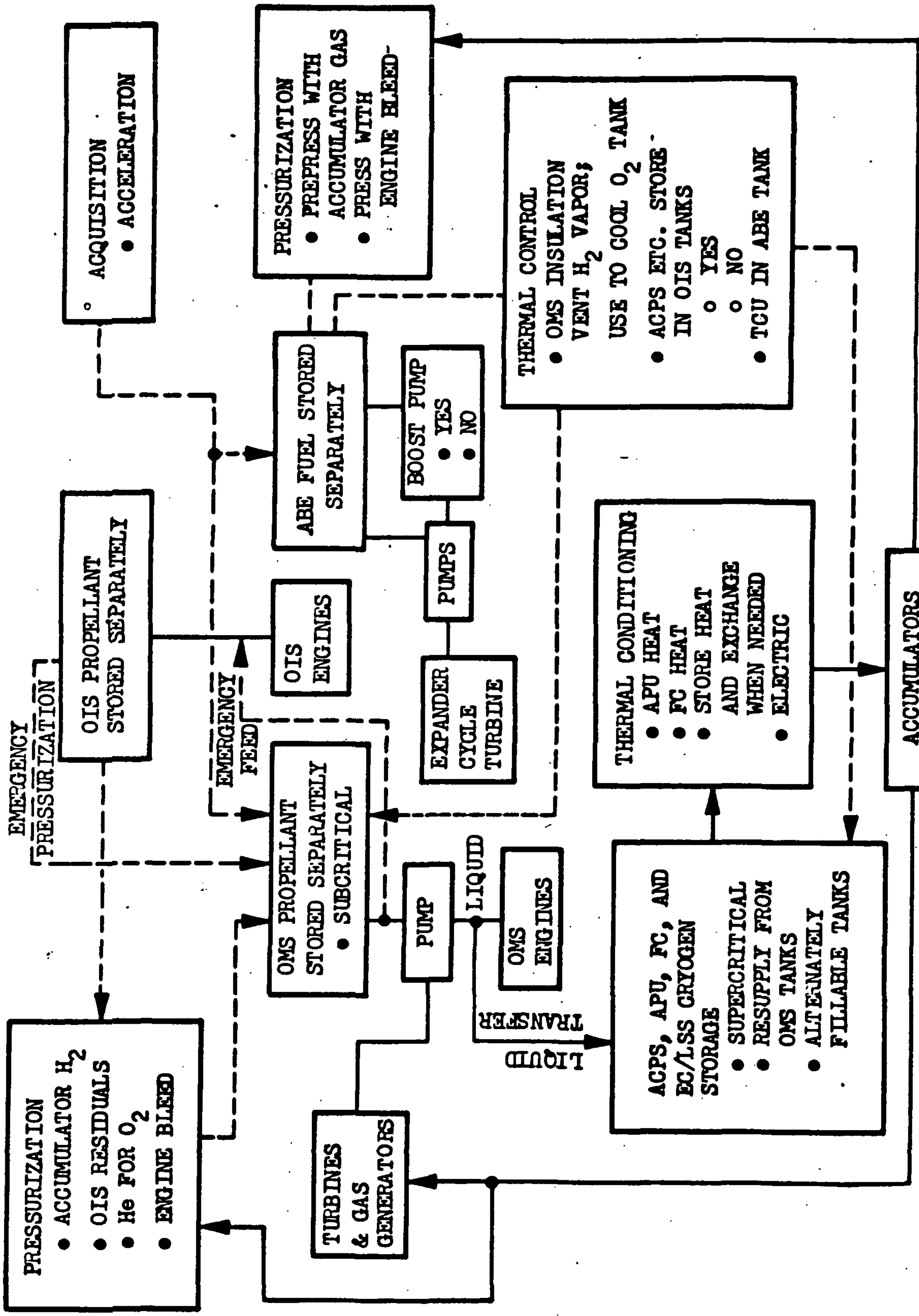

Fig. 10.2-19 Case 29: Integrate all Systems

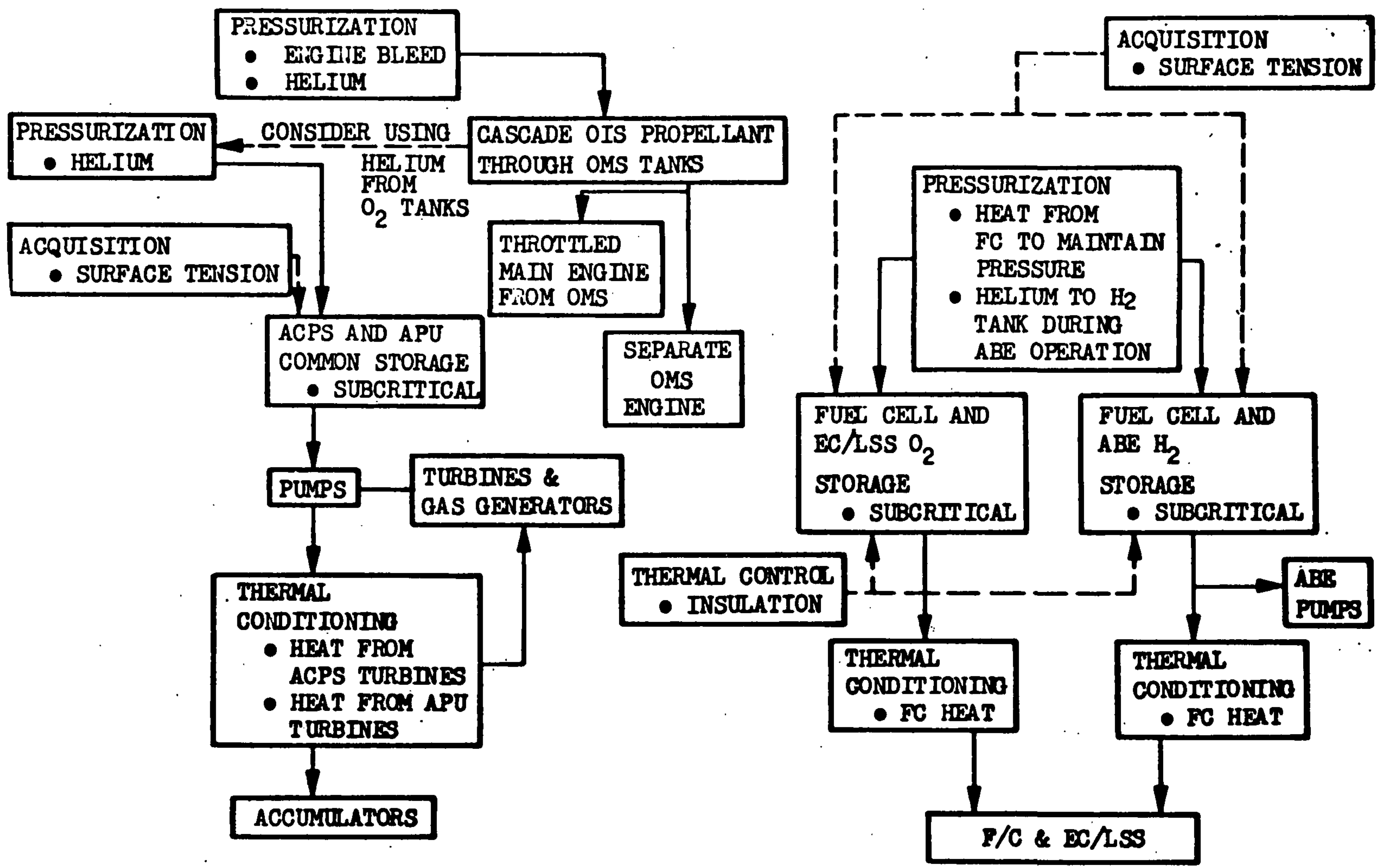

Fig. 10.2-20 Case 30: Integrate OIS and OMS; Integrate ACPS and APU; Integrate FC and ABE Hydrogen; Integrate FC and EC/LSS Oxygen

10.3 INTEGRATED SYSTEM ANALYSES

A major decision by NASA to utilize JP-fueled airbreathing engines instead of hydrogen-fueled engines resulted in the elimination of many of the cases shown in Figs. 10.1-1 and -2. The cases eliminated were 6, 7, 8, 10 through 17, and 19.

Several approaches were taken to analyze the remaining combinations. Obviously, every combination that can be formed by the selection of each concept, listed in Table 10.1-1 for each case and major mode of integration, could not be investigated. Therefore, preliminary schematics were formed that contained the more reasonable and desirable concepts and ideas. At the same time, analyses of the individual subsystems were being conducted and component listings were being generated.

Because the number and arrangement of components were important aspects of the integrated concepts, an approach was developed whereby the schematics and component listings of the individual subsystems were simply combined. The components that were common to more than one subsystem were eliminated, and additional components required for the specific integration were added. This approach is represented by the combined schematics shown in Fig. 10.3-1. A pump feed system, utilizing common tanks for storage of all subsystem cryogens, shows single-thread concepts. However, in performing the component counts and in obtaining the weights of the integrated systems, subsystems employing redundant components capable of meeting the fail-operation/fail-safe criteria were utilized.

The integrated systems selected for analyses were based upon the degree of common storage; i.e., the integrated systems having all cryogens stored in common subcritical tanks were evaluated first. Combinations having less degree of commonality were then evaluated. These systems, shown in Table 10.3-1, present the systems arrangement in order of storage commonality, with the subcritical storage being listed first and moving on to less-storage commonality and/or more supercritical storage. Supercritical storage

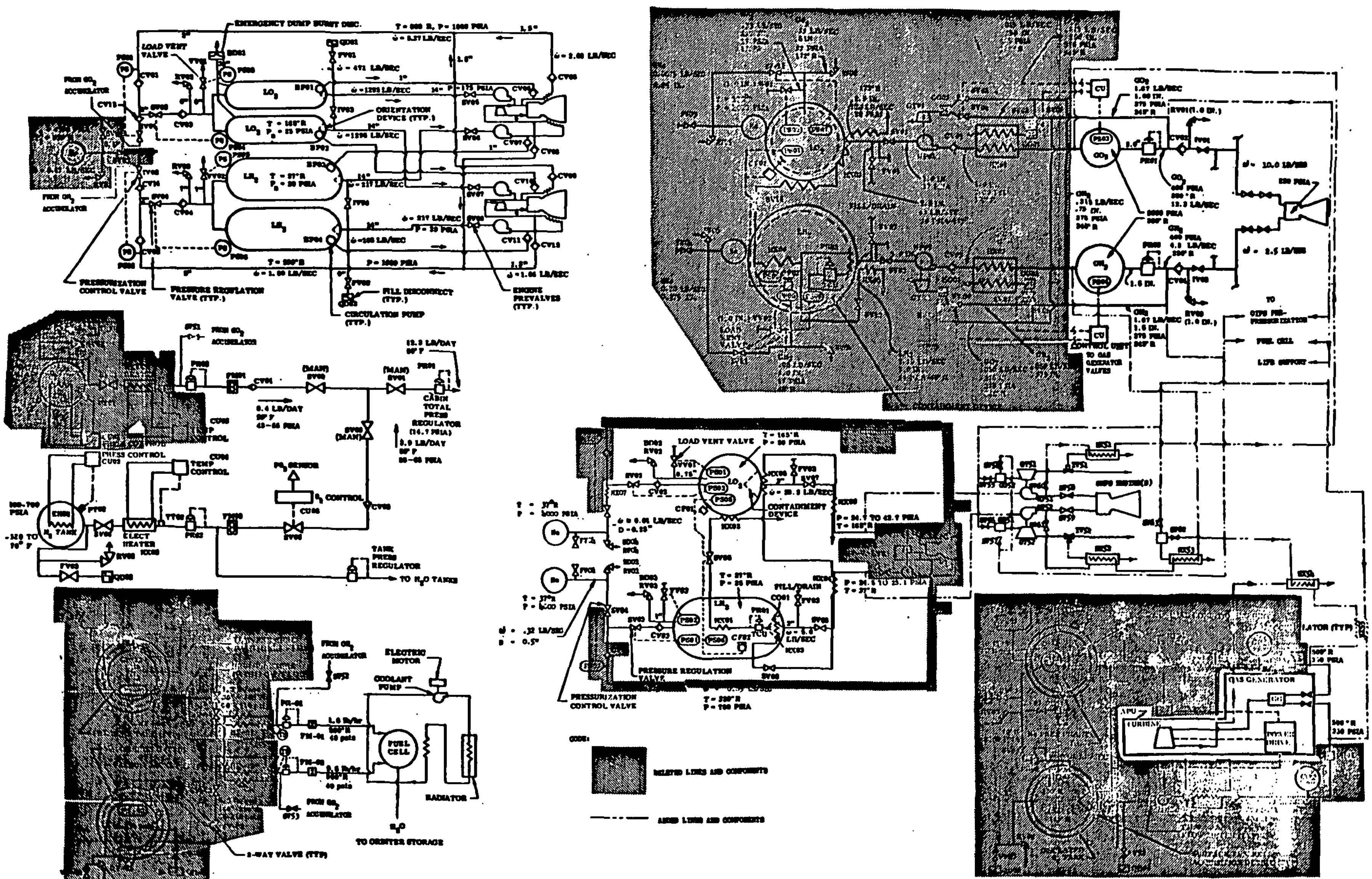

Fig. 10.3-1 All Systems Integrated - Subcritical Storage, Pump Fed

Table 10.3-1

INTEGRATED SYSTEMS

	I	II	III	IV	V	VI	VII	VIII	REF
SUBCRITICAL	OMPS ACPS APU FC EC/LSS	OMPS ACPS APU	OMPS ACPS APU	OMPS ACPS	OMPS ACPS APU FC EC/LSS	OMPS	OMPS ACPS APU	OMPS	OMPS ACPS APU
SUPERCRITICAL		FC EC/LSS	FC EC/LSS	APU FC EC/LSS		ACPS APU FC EC/LSS	FC EC/LSS	ACPS APU FC EC/LSS	FC EC/LSS
SYSTEM WEIGHT									
DRY (INERT) WT	8,678	9,155	8,695	9,373	8,854	12,705	9,410	12,424	9,936
CRYOGENS	40,020	39,803	39,415	39,780	40,549	41,035	39,691	40,365	39,754
TOTAL	48,698	48,958	48,110	49,153	49,403	53,740	49,101	52,789	49,690
NO. OF COMPONENTS	375	451	679	608	433	431	519	488	774
CASE	29-2	19 + 30	3 + 30	22	27-1	29-1	30-2	30-1	

ALL CASES INCLUDE OIPS FEED AND FILL COMPONENT WEIGHTS BUT NOT INCLUDED IN COMPONENT

DC3517

somewhat implies a lesser degree of integration, because the orbit maneuvering propellant is never assumed to be stored supercritically because of the large weight penalties that would result.

Boxes in this table enclose those systems whose cryogens are stored in common tanks. For System I, all the cryogens are stored in subcritical common tankage. For System II, the fuel cell and life-support cryogens are stored in common supercritical tankage that is separate from the rest of the systems. This arrangement continues for eight different systems. The case numbers to which these systems apply are shown on the bottom of the chart.

Also, the weight and total number of components of each system are shown. These weights are based upon a nominal set of usable cryogens, as shown in Table 10.3-2. For most of the analyses, these nominal quantities were employed; however, the range of maximum and minimum shown previously also were considered to make sure that general trends and conclusions were still applicable to different combinations of cryogen weights.

The Orbit Injection Propellant Supply (OIPS) System is considered a separate system, except for supplying its prepressurant from the ACPS accumulators, crossfeeding from the OMPS System for abort modes, and utilizing residuals for environmental control cooling. The weights shown in the table include the feed and pressurization portion of the OIPS only.

The number of components was determined by utilizing the subsystem detail listing of components, including the redundance required to satisfy the fail-operational/fail-safe criteria. When subsystems were combined, a number of components were eliminated. This is exemplified by comparing the number of components for each system listed with the reference system shown in the last column. This reference system was chosen by selecting light weight and simple individual subsystems. The OIPS system components are not included in the number shown on the table. When baseline subsystems and integrated systems were finalized, slight changes in the number of components

Table 10.3-2

CRYOGEN WEIGHTS USED FOR COMPARISONS

	O_2	H_2	I_{sp}
OIPS	450,000	75,000	
OMPS	23,128	4,626	444 (1)
ACPS (2) (3)	5,793 (4)	1,645	379 SS., 341 pulsing MR = 3.52
APU (5)	408	454	P = 300 psia, MR = 0.9
FC (6)	1,475	175	
EC/LSS	50		

(1) Based on RL-10 I_{sp} for comparison - higher values can be readily achieved

(2) Based on a Δ V split which devotes 185 ft/sec to the ACPS

(3) Total impulse = 1,687,000 lb/sec S.S., 1,018,000 lb/sec pulsing

(4) These values resolve to O_2 = 5,230 and H_2 = 1,310 delivered at the thruster for I_{sp} = 430 S.S. and 388 pulsing

(5) Other values used depending on integration modes at MR = 0.9:

Turbine Pressure (psi)	O_2 (lb)	H_2 (lb)
900	282	314
600	294	327
300	408	454

(6) Near the maximum was used. Current nominal values are approximately 750 lb total.

and weights resulted. These new values were not cycled back through the systems shown here; however, the values shown are correct for comparisons.

The systems listed in Table 10.3-1 can have slightly different arrangements, which require more description of the system elements. In analyzing the systems, several elements seemed to continually show up as major design features. These were somewhat different than those originally described in the early definition of potential integrated systems. The primary elements are:

- Storage
- Pump-type and location
- Pressurization type, with or without vacuum jackets
- Type of acquisition system

These elements were used to further describe the integrated systems listed in Table 10.3-1. For example, System I and two alternate systems are described in Table 10.3-3. The primary system, shown as System Ia, consists of all cryogens stored in common subcritical tankage. In this system: (1) all cryogens are passed through a common set of pumps with liquid-fed OMPS thrusters and gas-fed ACPS thrusters; (2) helium is used for pressurization; (3) vacuum-jacketed tanks are provided; and (4) the acquisition subsystem is compartmented with screened heads.

This compartment is obtained by placing a bulkhead with screened holes in it in the aft portion of the cylindrical-hemispherical hydrogen tank; thus, a smaller tank containing the acquisition device is created. The device consists of cylindrical channels with seven, screened acquisition heads attached.

Table 10.3-3

INTEGRATED SYSTEM I

STORE	PUMP	PRESSUR-IZATION	VACUUM JACKET	ACQUISITION
SUBCRITICAL OMPS ACPS APU FC EC/LSS	**COMMON AT TANK** OMPS ACPS APU FC EC/LSS	**HELIUM** OMPS ACPS APU FC EC/LSS	**YES** OMPS ACPS APU FC EC/LSS	**COMPARTMENT WITH HEADS** OMPS ACPS APU FC EC/LSS
SUBCRITICAL OMPS ACPS APU FC EC/LSS	**SEPARATE AT ENGINE** OMPS **COMMON AT TANK** ACPS APU FC EC/LSS	**HELIUM** OMPS ACPS APU FC EC/LSS	**YES** OMPS ACPS APU FC EC/LSS	**COMPARTMENT WITH HEADS** OMPS ACPS APU FC EC/LSS
SUBCRITICAL OMPS ACPS APU FC EC/LSS	**SEPARATE AT ENGINE** OMPS **COMMON AT TANK** ACPS APU FC EC/LSS	**HELIUM** OMPS ACPS APU FC EC/LSS	**NO** OMPS ACPS APU FC EC/LSS	**START TANK WITH HEAD** OMPS ACPS APU FC EC/LSS

The weight statement for System Ia is shown in Tables 10.3-4 and -5.

Also shown in Table 10.3-3 is an alternate for different pump arrangements. This system utilizes RL-10 engines for the OMPS operation and a separate pump for supplying the cryogens via heat exchangers and accumulators to the other systems. The weight of this system is shown in Tables 10.3-6 and -7.

Another alternate is shown in Table 10.3-3, which is similar to the MDC Phase B configuration. This system utilizes a start tank arrangement, and the weight summaries for this mode of integration are shown in Tables 10.3-8 and -9.

An estimate of the number of components for each system has been made and is shown in the weight summaries for each primary and alternate system as well as in the summary in Table 10.3-51.

A description of System II, with one alternate system (b), is shown in Table 10.3-10. Tables 10.3-11, -12, and -13 show the weight summaries for System IIa, and Tables 10.3-14 and -15 show the weight summaries for System IIb.

The description of System III is shown in Table 10.3-16. For this system, the only difference between the primary system (a) and the alternate system (b) is that the APU system uses either subcritically or supercritically stored reactants. The weights for System IIIa are shown in Tables 10.3-17 through -20. To complete the weight summary, the information for the supercritically integrated fuel cell and EC/LSS shown in Table 10.3-13 for System II should be added to this system.

An alternate for this system is presented in Tables 10.3-21 and -22, which show the data for the supercritically stored APU reactants. The other systems are the same.

Table 10.3-4

(Ia) INTEGRATED SUBCRITICAL OMPS + ACPS + APU + FC + EC/LSS

CRYOGEN WEIGHTS (LB)

	O_2	H_2	COMMENTS
OMPS	22,897	4,580	I_{SP_T} = 448 sec
ACPS	5,230	1,310	I_{SP_T} = Ave 410 sec
APU	294	327	MR = 0.9, P = 600 psia
FUEL CELL	1,450	175	
EC/LSS	50	-	
PREPRESSURANT	6	23	
CONDITIONING	1,019	1,019	
COOLING	-	504	
DUMPED	69	5	
LINE CHILLDOWN	12	8	
VENTED	-	161	
RESIDUALS (L)	402	100	
(G)	177	202	
TOTAL	31,606 lb	8,414 lb	

D03769

Table 10.3-5

(Ia) INTEGRATED SUBCRITICAL OMPS + ACPS + APU + FC + EC/LSS

INERT WEIGHTS (LB)

	WEIGHT	COMMENTS
O_2		
Tank	145	Sphere 10.4 ft, P = 20 psia
Insulation	20	0.8 in. Superfloc
Vacuum Jacket	202	
Accumulator	225	2,000 psia
Accumulator Residuals	150	Blowdown 2,000 to 750 psia
He + Tank	15	
H_2		
Tank	480	Cylinder 11.7 ft dia x 15 ft, P = 18 psia
Insulation	147	2 in. Superfloc
Vacuum Jacket	736	
Accumulator	650	2,000 psia
Accumulator Residuals	35	Blowdown 2,000 to 75 psia
He + Tank	114	
THRUSTERS (3)	300	F = 8K
Acquisition	267	Cruciform + interal bulkhead
Components	1,219	Includes 3 turbopumps
Lines	675	Includes lines to ACPS thruster
TOTAL	5,380 .lb	

D03768

Table 10.3-6

(Ib) INTEGRATED SUBCRITICAL OMPS + ACPS + APU + FC + EC/LSS – SEPARATE PUMPS

	CRYOGEN WEIGHTS (LB)		
	O_2	H_2	
OMPS	23,128	4,626	I_{SP} 444 sec
ACPS	5,230	1,310	
APU	294	327	
FUEL CELL	1,450	175	
EC/LSS	50		
PRE PRESS	6	23	
COND	675	675	
DUMPED	180	24	
COOLING (ACPS PUMP)		504	
LINE CHILLDOWN	52	50	
PUMP	30	24	
VENTED		158	
RESIDUALS (L)	403	97	
(G)	178	189	
TOTAL	31,676	8,182	

Table 10.3-7

(Ib) INTEGRATED SUBCRITICAL OMPS + ACPS + APU + FC + EC/LSS – SEPARATE PUMPS

	INERT WEIGHTS (LB)	
O_2 TANK	252	47 psi
INSULATION	25	
VACUUM JACKET	220	
ACCUMULATOR	225	
ACCUMULATOR RESIDUALS	150	
He + TANK	120	
H_2 TANK	575	24 psi
INSULATION	145	
VACUUM JACKET	775	
ACCUMULATOR	650	
ACCUMULATOR RESIDUALS	35	
He + TANK	249	
ENGINES	600	
ACQUISITION	267	
COMPONENTS (396)	1,152	
LINES	543	
	5,983	

Table 10.3-8

INTEGRATED SUBCRITICAL OMPS + ACPS + APU + FC + EC/LSS

CRYOGEN WEIGHTS (LB)

	O_2	H_2	COMMENTS
OMPS	23,128	4,626	444 SEC
ACPS	5,230	1,310	
APU	294	327	
FC	1,450	175	
EC/LSS	50		
PREPRESSURANT	6	23	
CONDITIONING	675	675	
DUMPED	180	24	
COOLING		504	
LINE CHILL	84	66	
ENGINE CHILL	30	24	
VENTED		271	
RESIDUALS (L)	398	93	
(G)	244	285	
TOTAL	31,769	8,403	

D04153

Table 10.3-9

INTEGRATED SUBCRITICAL OMPS + ACPS + APU + FC + EC/LSS

INERT WEIGHTS (LB)

	WEIGHT	COMMENTS
O_2 TANK	256	47 PSIA
INSULATION	26	
VACUUM JACKET	228	
ACCUMULATOR	225	
ACCUMULATOR RESIDUALS	150	
HE. + TANK	122	
H_2 TANK	995	37 PSIA
INSULATION	173	
START TANK	501	
INSULATION	55	
ACCUMULATOR	650	
ACCUMULATOR RESIDUALS	35	
HE. + TANK	101	
ENGINES	600	
ACQUISITION	131	
COMPONENTS (422)	1,312	
LINES	563	
TOTAL	6,123	

D04157

Table 10.3-10

INTEGRATED SYSTEM II

	STORE	PUMP	PRESSUR-IZATION	VACUUM JACKET	ACQUISITION
a)	SUBCRITICAL	COMMON AT TANK	HELIUM	YES	COMPARTMENT WITH HEADS
	OMPS ACPS APU	OMPS ACPS APU	OMPS ACPS APU	OMPS ACPS APU	OMPS ACPS APU
	SUPERCRITICAL	NONE	O_2 H_2	YES	NONE
	FC EC/LSS	FC EC/LSS	FC EC/LSS	FC EC/LSS	FC EC/LSS
b)	SUBCRITICAL	COMMON AT TANK	HELIUM	NO	START TANK WITH HEADS
	OMPS ACPS APU	OMPS ACPS APU	OMPS ACPS APU	OMPS ACPS APU	OMPS ACPS APU
	SUPERCRITICAL	NONE	O_2 H_2	YES	NONE
	FC EC/LSS	FC EC/LSS	FC EC/LSS	FC EC/LSS	FC EC/LSS

D04439

Table 10.3-11

(IIa) INTEGRATED SUBCRITICAL OMPS + ACPS + APU

	CRYOGEN WEIGHTS (LB)	
	O_2	H_2
OMPS	22,897	4,580
ACPS	5,230	1,310
APU	294	327
PRE PRESS	6	23
COND	928	928
COOLING		504
DUMPED	69	5
LINE CHILLDOWN	12	8
VENTED		157
RESIDUALS (L)	386	97
(G)	170	197
TOTAL	29,992	8,136

Table 10.3-12

(IIa) INTEGRATED SUBCRITICAL OMPS + ACPS + APU

	INERT WEIGHTS (LB)
O_2 TANK	139
INSULATION	24
VACUUM JACKET	208
ACCUMULATOR	225
ACCUMULATOR RESIDUALS	150
He + TANK	14
H_2 TANK	467
INSULATION	143
VACUUM JACKET	770
ACCUMULATOR	650
ACCUMULATOR RESIDUALS	35
He + TANK	111
THRUSTERS	300
ACQUISITION	260
COMPONENTS (305)	1125
LINES	662
	5283

Table 10.3-13

(IIa) INTEGRATED SUPERCRITICAL FC + EC/LSS

(O_2 Portion of EC/LSS Only)

	WEIGHT	COMMENTS
O_2		
Tank	156	P = 850 psi, T_{MAX} = 350°R
Insulation	4	Superfloc
Vacuum Jacket	14	
H_2		
Tank	24	P = 200 psi, T_{MAX} = 350°F
Insulation	6	Superfloc
Vacuum Jacket	23	
COMPONENTS (146)	215	
LINES (Estimate)	50	
O_2 RESIDUALS	20	
H_2 RESIDUALS	2	
CRYOGENS		
O_2	1,500	
H_2	175	
TOTAL	2,249 lb	

D03775

Table 10.3-14

(IIb) INTEGRATED SUBCRITICAL OMPS + ACPS + APU

CRYOGEN WEIGHTS (LB)

	O_2	H_2
OMPS	22,897	4,580
ACPS	5,230	1,310
APU	294	327
PREPRESSURANT	6	23
CONDITIONING	928	928
COOLING		504
DUMPED	69	5
LINE CHILL	12	8
VENTED		306
RESIDUALS (L)	386	92
(G)	170	239
TOTAL	29,992	8,322

D04154

Table 10.3-15

(IIb) INTEGRATED SUBCRITICAL OMPS + ACPS + APU

INERT WEIGHTS (LB)

	WEIGHT	COMMENTS
O_2 TANK	139	47 PSI
INSULATION	24	0.8-IN. SUPERFLOC
VACUUM JACKET	208	
ACCUMULATOR	225	
ACCUMULATOR RESIDUALS	150	
HE. + TANK	14	
H_2 TANK	845	31 PSI
INSULATION	172	2-IN. SUPERFLOC + PURGE BAG
START TANK	501	
INSULATION	55	
ACCUMULATOR	650	
ACCUMULATOR RESIDUALS	35	
HE. + TANK	84	
THRUSTERS	300	
ACQUISITION	128	
COMPONENTS	1,285	
LINES	682	
TOTAL	5,497	

D04152

Table 10.3-16

INTEGRATED SYSTEM III

	STORE	PUMP	PRESSUR-IZATION	VACUUM JACKET	ACQUISITION
a)	SUBCRITICAL OMPS ACPS	COMMON AT TANK OMPS ACPS	HELIUM OMPS ACPS APU	NO OMPS ACPS	COMPARTMENT WITH HEADS OMPS ACPS
	SUBCRITICAL APU	SEPARATE AT APU APU	O_2 H_2 FC EC/LSS	YES APU FC EC/LSS	WITH HEADS APU
	SUPERCRITICAL FC EC/LSS	NONE FC EC/LSS			NONE FC EC/LSS
b)	SUBCRITICAL OMPS ACPS	COMMON AT TANK OMPS ACPS	HELIUM OMPS ACPS	NO OMPS ACPS	COMPARTMENT WITH HEADS OMPS ACPS
	SUPERCRITICAL APU FC EC/LSS	NONE APU FC EC/LSS	O_2 H_2 APU FC EC/LSS	YES APU FC EC/LSS	NONE APU FC EC/LSS

Table 10.3-17

(IIIa) INTEGRATED OMPS + ACPS

	CRYOGEN WEIGHTS (LB)		
	O_2	H_2	COMMENTS
OMPS IMPULSE	22,500	4,500	(I_{SP_T} = 456)
ACPS IMPULSE	5,230	1,310	(I_{SP_T} = 430_{MAX}, 410_{AVE})
CONDITIONING	938	938	(443 OMPS)
CHILLDOWN	16	8	
DUMPED	69	5	
LIQUID RESIDUAL	290	74	
GAS RESIDUAL	280	183	
PUMP COOLING	-	504	
BOILOFF	-	158	
TOTAL	29,323	7,680	

D03472

Table 10.3-18

(IIIa) INTEGRATED OMPS + ACPS

	INERT WEIGHTS (LB)
O_2 TANK	147
INSULATION	46
ACCUMULATOR	225
ACCUMULATOR RESIDUALS	150
He + TANK	15
H_2 TANK	534
INSULATION	161
ACCUMULATOR	650
ACCUMULATOR RESIDUALS	35
He + TANK	111
THRUSTERS	300
ACQUISITION	230
COMPONENTS (242)	897
LINES	445
	3,946

Table 10.3-19
(IIIa) APU SYSTEM - SUBCRITICAL

	CRYOGEN WEIGHTS (LB)	
	O_2	H_2
USEABLE	282	314
CONDITIONING	41	41
PUMP	12	12
VENTED		25
RESIDUALS (L)	3	3
(G)	1	13
TOTAL	329	408

Table 10.3-20

(IIIa) APU SYSTEM - SUBCRITICAL

	INERT WEIGHTS (LB)	
O_2 TANK	9	25 psi
INSULATION	2	
VACUUM JACKET	5	
ACCUMULATOR	3	Start Tank
ACCUMULATOR RESIDUALS	2	
H_2 TANK	39	25 psi
INSULATION	24	
VACUUM JACKET	43	
ACCUMULATOR	39	Start Tank
ACCUMULATOR RESIDUALS	1	
He + TANK	4	
ACQUISITION	21	
COMPONENTS (291)	650	
LINES (ESTIMATE)	35	
	877	

Table 10.3-21

(IIIb) APU SYSTEM - SUPERCRITICAL

	CRYOGEN WEIGHTS (LB)	
	O_2	H_2
USEABLE	294	327
CONDITIONING	58	58
VENTED		15
RESIDUALS	19	57
TOTAL	371	457

Table 10.3-22

(IIIb) APU SYSTEM - SUPERCRITICAL

	INERT WEIGHTS (LB)
O_2 TANKS	48
INSULATION	2
VACUUM JACKET	5
ACCUMULATOR	9
H_2 TANKS	624
INSULATION	28
VACUUM JACKET	47
ACCUMULATOR	35
COMPONENTS (234)	765
LINES	38
	1,601

The description of System IV is shown in Table 10.3-23 along with two alternates. Weight summaries for the primary system are shown in Tables 10.3-24 and -25; the alternate (b) weights are presented in Tables 10.3-26 and -27. System IV(c) is most like the NAR Phase B system, and the weights are shown in Tables 10.3-28 and -29.

A description of System V is shown in Table 10.3-30 along with one alternate. Weight summaries for the OMPS are shown in Tables 10.3-31 and -32 and for the integrated subcritically stored ACPS, APU, FC, and EC/LSS in Tables 10.3-33 and -34. System V(b) differs from V(a) in that the pressurization system uses helium rather than gaseous propellants, and the integrated ACPS, APU, FC, and EC/LSS system is not required to feed pressurization gas to the OMPS. The weights are shown in Tables 10.3-35 and -36 for the OMPS system and in Tables 10.3-37 and -38 for the ACPS, APU, FC, and EC/LSS integrated system.

Integrated System VI, with one alternate, is described in Table 10.3-39. The weight summary for the OMPS is the same as System V (Tables 10.3-31 and -32). The weight summary for the supercritical ACPS, APU, FC, and ES/LSS is presented in Tables 10.3-40 and -41. System VI(b) represents an option for refilling the supercritical ACPS, APU, FC and EC/LSS tanks; details of the refill process are discussed later. Weight changes to the system are shown in Table 10.3-42; the weight increment shown can be applied to System II(a), whose weight is given in Tables 10.3-31 and -32 for the OMPS and Tables 10.3-33 and -34 for the supercritical ACPS, APU, FC, and EC/LSS. The resulting weights will be representative of the weight of System VI(b).

The description of System VII is shown in Table 10.3-43; no alternates are shown for this particular combination. Weight summaries are shown in Tables 10.3-44 and -45 for the OMPS and Table 10.3-46 for the subcritical ACPS and APU. The supercritical FC and EC/LSS weights are shown in System II (Table 10.3-13).

Table 10.3-23

INTEGRATED SYSTEMS IV

	Systems	STORE	PUMP	PRESSURIZATION	VACUUM JACKET	ACQUISITION
a)	OMPS, ACPS	SUBCRITICAL	COMMON AT TANK	HELIUM	NO	COMPARTMENT WITH HEADS
	APU, FC, EC/LSS	SUPERCRITICAL	NONE	O_2 H_2	YES	NONE
b)	OMPS, ACPS	SUBCRITICAL	COMMON AT TANK	HELIUM	NO	START TANK WITH HEADS
	APU, FC, EC/LSS	SUPERCRITICAL	NONE	O_2 H_2	YES	NONE
c)	OMPS, ACPS	SUBCRITICAL	COMMON AT TANK	HELIUM	YES	COMPARTMENT WITH HEADS
	APU, FC, EC/LSS	SUPERCRITICAL	NONE	O_2 H_2	YES	NONE

D04441

Table 10.3-24

(IVa) INTEGRATED APU, FC, EC/LSS

	CRYOGEN WEIGHTS (LB)		
	O_2	H_2	
APU	408	454	MR = .9 P = 300 psia
CONDITIONING	31	31	
FUEL CELL	1,450	175	
EC/LSS	50	-	
RESIDUALS	84	94	
TOTAL	2,023	754	

Table 10.3-25

(IVa) INTEGRATED APU, FC, EC/LSS

	INERT WEIGHTS (LB)	
O_2 TANK	237	P = 850
INSULATION	5	
VACUUM JACKET	17	
ACCUMULATOR	10	
H_2 TANK	789	P = 350
INSULATION	48	
VACUUM JACKET	80	
ACCUMULATOR	39	
COMPONENTS (366)	834	
LINES	70	
	2,129	

Table 10.3-26

(IVb) INTEGRATED OMPS + ACPS

CRYOGEN WEIGHTS (LB)

	O_2	H_2	COMMENTS
OMPS	22,500	4,500	(I_{SP_T} = 456)
ACPS	5,230	1,310	
CONDITIONING	938	938	
CHILLDOWN	16	8	
DUMPED	69	5	
VENTED		286	
RESIDUALS (L)	290	80	
(G)	280	223	
TOTAL	29,323	7,350	

D04151

Table 10.3-27

(IVb) INTEGRATED OMPS + ACPS

INERT WEIGHTS (LB)

	WEIGHT
O_2 TANK	147
INSULATION	46
ACCUMULATOR	225
ACCUMULATOR RESIDUALS	150
HE. + TANK	15
H_2 TANK	792
INSULATION	161
START TANK	462
INSULATION	52
ACCUMULATOR	650
ACCUMULATOR RESIDUALS	35
HE. + TANK	84
THRUSTERS	300
ACQUISITION	122
COMPONENTS	1,057
LINES	465
TOTAL	4,763

D04162

Table 10.3-28

(IVc) INTEGRATED OMPS + ACPS

CRYOGEN WEIGHTS (LB)

	O_2	H_2
OMPS IMPULSE	22,500	4,500
ACPS	5,230	1,310
CONDITIONING	938	938
COOLING		504
CHILLDOWN	16	8
DUMPED	69	5
VENTED		158
RESIDUALS (L)	290	74
(G)	280	183
TOTAL	29,323	7,680

D04156

Table 10.3-29

(IVc) INTEGRATED OMPS + ACPS

INERT WEIGHTS (LB)

	WEIGHT
O_2 TANK	135
INSULATION	23
VACUUM JACKET	208
ACCUMULATOR	225
ACCUMULATOR RESIDUALS	150
HE. + TANK	15
H_2 TANK	444
INSULATION	122
VACUUM JACKET	743
ACCUMULATOR	650
ACCUMULATOR RESIDUALS	35
HE. + TANK	111
THRUSTERS	300
ACQUISITION	230
COMPONENTS	897
LINES	445
TOTAL	4,733

D04155

Table 10.3-30

INTEGRATED SYSTEM V

	STORE	PUMP	PRESSURIZATION	VACUUM JACKET	ACQUISITION
a)	SUBCRITICAL	SEPARATE AT ENGINE	GO_2 GH_2	NO	START CONTAINER
	OMPS	OMPS	OMPS	OMPS	OMPS
		COMMON AT TANK	HELIUM	YES	CHANNELS & HEADS
	ACPS APU FC EC/LSS	ACPS APU FC EC/LSS	ACPS APU FC EC/LSS	ACPS APU FC EC/LSS	ACPS APU FC EC/LSS
b)	SUBCRITICAL	SEPARATE AT ENGINE	HELIUM	NO	START CONTAINER
	OMPS	OMPS	OMPS	OMPS	OMPS
		COMMON AT TANK		YES	CHANNELS & HEADS
	ACPS APU FC EC/LSS	ACPS APU FC EC/LSS	ACPS APU FC EC/LSS	ACPS APU FC EC/LSS	ACPS APU FC EC/LSS

D04442

Table 10.3-31

(Va) INTEGRATED OMPS

CRYOGEN WEIGHTS (LB)

	O_2	H_2	
IMPULSE	23,128	4,626	$I_{SP} = 444$
RESIDUALS (L)	317	67	
(G)	240	171	
DUMPED	180	24	
VENTED		186	
LINE CHILL	84	66	
ENGINE CHILL	30	24	
TOTAL	23,979	5,164	

Table 10.3-32

(Va) INTEGRATED OMPS

	INERT WEIGHTS (LB)
O_2 TANK	218
INSULATION	36
H_2 TANK	535
INSULATION	113
ENGINES	600
ACQUISITION	60
COMPONENTS (129)	454
LINES	68
	2,084

Table 10.3-33

(Va) INTEGRATED SUBCRITICAL ACPS + APU + FC + EC/LSS

CRYOGEN WEIGHTS (LB)

	O_2	H_2	COMMENTS
ACPS	5,230	1,310	I_{SP_T} = 430 sec, 410 Ave
APU	294	327	MR = 0.9, P = 600 psi
FC	1,450	175	
EC/LSS	50	-	
OIPS PREPRESSURANT	6	23	
OMPS PREPRESSURANT	420	6	
CONDITIONING	700	700	T = 250°R H_2, 380°R O_2
COOLING	-	504	Pump Cooling
RESIDUALS (L)	83	33	
RESIDUALS (G)	39	56	
TOTAL	8,272 lb	3,134 lb	

D03770

Table 10.3-34

(Va) INTEGRATED SUBCRITICAL ACPS + APU + FC + EC/LSS

INERT WEIGHTS (LB)

	WEIGHT	COMMENTS
O_2		
Tank	52	Sphere, P = 35 psia
Insulation	8	0.8 in. Superfloc
Vacuum Jacket	57	
Accumulator	225	2,000 to 1,000 psi 380°R (2,219)
He and Tank (11 + 3.2)	14	Ti - 4000 psi, T = 165°R
Accumulator Residuals	216	
H_2		
Tank	179	Sphere, P = 28 psia
Insulation	69	2 in. Superfloc
Vacuum Jacket	245	
Accumulator	650	2,000 to 1,000 psi, 250°R (421/427)
He and Tank (43 + 74)	117	Ti - 4000 psi, T = 38°R
Accumulator Residuals	32	
ACQUISITION	155	
COMPONENTS (304)	1,067	
LINES	386	
TOTAL	3,472	
CRYOGENS	11,406	
TOTAL	14,878 lb	

D03772

Table 10.3-35

(Vb) INTEGRATED OMPS

CRYOGEN WEIGHTS (LB)

	O_2	H_2
IMPULSE	23,128	4,626
RESIDUALS (L)	320	68
(G)	138	215
DUMPED	180	24
VENTED		116
LINE CHILL	78	75
ENGINE	30	24
TOTAL	23,874	5,148

D04161

Table 10.3-36

(Vb) INTEGRATED OMPS

INERT WEIGHTS (LB)

	WEIGHT
O_2 TANKS	202
INSULATION	37
HE. + TANK	97
H_2 TANK	478
INSULATION	118
HE. + TANK	177
ENGINES	600
ACQUISITION	60
COMPONENTS	300
LINES	57
TOTAL	2,126

D04160

Table 10.3-37

(Vb) INTEGRATED SUBCRITICAL ACPS + APU + FC + EC/LSS

CRYOGEN WEIGHTS (LB)

	O_2	H_2
ACPS	5,230	1,310
APU	294	327
FC	1,450	175
EC/LSS	50	-
OIPS PREPRESSURANT	6	23
CONDITIONING	685	685
COOLING		504
RESIDUALS (L)	83	33
(G)	39	56
TOTAL	7,837	3,113

D04158

C-2.

Table 10.3-38

(Vb) INTEGRATED SUBCRITICAL ACPS + APU + FC + EC/LSS

INERT WEIGHTS (LB)

	WEIGHT
O_2 TANK	49
INSULATION	8
VACUUM JACKET	55
ACCUMULATOR	225
ACCUMULATOR RESIDUALS	216
HE. + TANK	14
H_2 TANK	178
INSULATION	69
VACUUM JACKET	243
ACCUMULATOR	650
ACCUMULATOR RESIDUALS	32
HE. + TANK	117
ACQUISITION	155
COMPONENTS	1,067
LINES	376
TOTAL	3,454

D04159

Table 10.3-39

INTEGRATED SYSTEM VI

	STORE	PUMP	PRESSUR-IZATION	VACUUM JACKET	ACQUISITION
a)	SUBCRITICAL OMPS	SEPARATE AT ENGINE OMPS	GO_2 GH_2 OMPS	NO OMPS	START CONTAINER OMPS
	SUPERCRITICAL ACPS APU FC EC/LSS	NONE ACPS APU FC EC/LSS	GO_2 GH_2 ACPS APU FC EC/LSS	YES ACPS APU FC EC/LSS	NONE ACPS APU FC EC/LSS
b)	SUBCRITICAL OMPS REFILL ACPS APU FC EC/LSS	SAME PLUS REFILL PUMP PUMP AT OMPS TANK	HELIUM OMPS	NO OMPS	COMPARTMENTED WITH HEADS OMPS
	SUPERCRITICAL ACPS APU FC EC/LSS LESS REFILL		GO_2 GH_2 ACPS APU FC EC/LSS	YES ACPS APU FC EC/LSS	NONE ACPS APU FC EC/LSS

D04443

Table 10.3-40

(VIa) INTEGRATED SUPERCRITICAL ACPS + APU + FC + EC/LSS

	Cryogen Weights (lb) O_2	Cryogen Weights (lb) H_2	COMMENTS
ACPS	5,230	1,310	I_{SP_T} = 430 sec SS, 388-sec pulsing
APU	408	454	MR = 0.9, P = 300 psia
FC	1,450	175	
EC/LSS	50		
OIPS Prepressurant	6	23	Inlet Temp = 250°R H_2, 350°R O_2
OMPS Prepressurant	420	6	Inlet Temp = 250°R H_2, 350°R O_2
Settling	370	90	
Conditioning	591	591	T = 250°R H_2, 390°R O_2
Residuals	515	203	
TOTAL	9,040 lb	2,852 lb	

DO 3774

Table 10.3-41

(VIa) INTEGRATED SUPERCRITICAL ACPS + APU + FC + EC/LSS

Inert Weights (lb)

	WEIGHT	COMMENTS
O_2		
Tank	1,070	P = 850 psia
Insulation	61	0.8 in. Superfloc
Vacuum-Jacket	59	
Accumulator	47	Minimum pressure = 450 psia
Accumulator Residuals	33	
H_2		
Tank	3,790	P = 600 psia
Insulation	61	2 in. Superfloc
Vacuum-Jacket	217	
Accumulator	401	Minimum pressure = 450 psia
Accumulator Residuals	25	
ACPS Components (140)	747	
APU Components (63)	228	
FC Components (52)	78	
FC Heat Transfer Sys (29)	61	
EC/LSS (18)	12	
Lines	433	Includes lines to prepressurize OMPS and OIPS
TOTAL	7,323 lb	

Table 10.3-42

REFILL COMPARISON FOR ACPS + FC + APU + EC/LSS

	NO REFILL	REFILL	WT
O_2 TANK	1,020	280	-740
INSULATION	8	3	-5
VACUUM JACKET	59	16	-43
H_2 TANK	3,600	2,240	-1,360
INSULATION	61	39	-22
VACUUM JACKET	217	138	-79
O_2 RESIDUAL	515	113	-402
H_2 RESIDUAL	203	72	-131
ADDED COMPONENTS	-	370	+370
ADDED CONDITIONING	-	53	+53
ADDED STORAGE, OMPS TANKS	-	123	+123
ACQUISITION	-	200	+200
TOTAL WEIGHT SAVINGS			2,036 LB

Table 10.3-43

INTEGRATED SYSTEM VII

STORE	PUMP	PRESSURIZATION	VACUUM JACKET	ACQUISITION
SUBCRITICAL / OMPS	SEPARATE AT ENGINE / OMPS	HELIUM / OMPS	NO / OMPS	START CONTAINER / OMPS
SUBCRITICAL / ACPS APU	COMMON AT TANK / ACPS APU	HELIUM / ACPS APU	YES / ACPS APU	CHANNELS & HEADS / ACPS APU
SUPERCRITICAL / FC EC/LSS	NONE / FC EC/LSS	O_2 & H_2 / FC EC/LSS	YES / FC EC/LSS	NONE / FC EC/LSS

Table 10.3-44

(VII) INTEGRATED OMPS

	CRYOGEN WEIGHTS (LB)	
	O_2	H_2
IMPULSE	23,128	4,626
RESIDUALS (L)	320	68
(G)	138	215
DUMPED	180	24
VENTED		116
LINE CHILLDOWN	78	75
ENGINE CHILL	30	24
TOTAL	23,874	5,148

Table 10.3-45

(VII) INTEGRATED OMPS

	INERT WEIGHTS (LB)
O_2 TANK	202
INSULATION	37
He + TANK	97
H_2 TANK	478
INSULATION	118
He + TANK	177
ENGINES	600
ACQUISITION	60
COMPONENTS (139)	302
LINES	57
	2,128

Table 10.3-46

(VII) INTEGRATED SUBCRITICAL ACPS + APU

	INERT WEIGHT (lb)
O_2	
Tanks	48
Insulation	7
Vacuum Jacket	47
Accumulator	225
He and Tank	11
Accumulator Residuals	216
H_2	
Tanks	173
Insulation	64
Vacuum Jacket	228
Accumulator	650
He and Tank	104
Accumulator Residuals	155
ACQUISITION	138
COMPONENTS (234)	973
LINES	371
TOTAL	3,410
CRYOGENS	8,994
TOTAL	12,404 lb

CRYOGEN WEIGHT (lb)	O_2	H_2
ACPS	5,230	1,310
APU	294	327
CONDITIONING	580	580
COOLING	-	504
RESIDUALS (L)	62	29
(G)	29	49
TOTAL	6,195 lb	2,799 lb

D03776

A description of System VIII is shown in Table 10.3-47. The weight summaries for the OMPS are the same as for System V (Tables 10.3-31 and -32). The supercritical FC and EC/LSS weights are shown in System II (Table 10.3-13). Weight summaries for the supercritical ACPS and APU are shown in Tables 10.3-48 and -49.

The description of the reference subsystems is shown in Table 10.3-50. The systems and their alternates are summarized in Table 10.3-51.

In addition to the weight statements and component counts, other operational and safety aspects of the systems were considered. Table 10.3-52 presents a matrix of integrated systems and important parameters that influence the design or operation of the particular subsystem. Each element of the matrix has been assigned a judgement term that has meaning in a relative sense to elements of a particular row. Many evaluations of this nature are done by assigning weighted numbers to each element, adding the total and defining a "best system" based upon the highest number thus obtained. This approach was avoided, since it merely transforms the evaluators bias to an earlier stage of the comparison and tends to be misleading.

Table 10.3-47

INTEGRATED SYSTEM VIII

	STORE	PUMP	PRESSUR-IZATION	VACUUM JACKET	ACQUISITION
	SUBCRITICAL	SEPARATE AT ENGINE	GO_2 GH_2	NO	START CONTAINER
	OMPS	OMPS	OMPS	OMPS	OMPS
	SUPERCRITICAL	NONE	O_2 H_2	YES	NONE
	ACPS APU	ACPS APU	ACPS APU	ACPS APU	ACPS APU
	FC EC/LSS	FC EC/LSS	FC EC/LSS	FC EC/LSS	FC EC/LSS

Table 10.3-48

(VIII) INTEGRATED SUPERCRITICAL ACPS + APU

CRYOGEN WEIGHTS (LB)

	O_2	H_2	COMMENTS
ACPS	5,230	1,310	$P_C = 250$ I_{SP_T} 410 Ave
APU	408	454	MR = 0.9, P = 300 psia
CONDITIONING	525	525	T = 250°R H_2, 350°R O_2
RESIDUALS	415	187	P =450, T = 250° H_2, 350°R O_2
TOTAL	6,578 lb	2,476 lb	
OIPS PREPRESSURANT	6	23	
OMPS PREPRESSURANT	420	6	
CONDITIONING	19	19	
TOTAL	7,023 lb	2,524 lb	

D03771

Table 10.3-49

(VIII) INTEGRATED SUPERCRITICAL ACPS + APU

INERT WEIGHTS (LB)

	WEIGHT	WITH OIPS AND OMPS PREPRESSURIZATION
O_2		
Tanks	783	836
Insulation	7	7
Vacuum Jacket	47	49
Accumulator	47	47
Accumulator Residuals	33	33
H_2		
Tanks	3,340	3,410
Insulation	56	57
Vacuum Jacket	200	203
Accumulator	400	400
Accumulator Residuals	25	25
COMPONENTS (203)	975	975
LINES	401	426
TOTAL	6,314	6,468
CRYOGENS	9,054	9,547
TOTAL	15,368 lb	16,015 lb

D03777

Table 10.3-50

REFERENCE SYSTEM

	STORE	PUMP	PRESSUR-IZATION	VACUUM JACKET	ACQUISITION
OMPS	SUBCRITICAL	SEPARATE AT ENGINE	HELIUM	NO	START CONTAINER
ACPS		SEPARATE AT TANK		YES	CHANNELS & HEADS
APU		SEPARATE WITH APU			
FC	SUPERCRITICAL	NONE	O_2 H_2	FC EC/LSS	NONE
EC/LSS					

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Integrated Systems	Ia	Ib	Ic
Subsystem	Inert/ Cryogens	Inert/ Cryogens	Inert/ Cryoge
OIPS	3,298	3,298	3,298
OMPS			
ACPS			
APU	5,380/ 40,020	5,983 39,858	6,123 40,17
FC			
EC/LSS			
TOTAL	8,678/ 40,020	9,281/ 39,858	9,421/ 40,172
Number of Components(1)	375	396	422

(1) Does not include OIPS components.

2.
FOLDOUT FRAME)

Table 10.3-51

SUMMARY OF WEIGHTS AND COMPONENTS

Ib	Ic	IIa	IIb	IIIa	IIIb	IVa	IVb	IVc	
Inert/ Cryogens	Inert/ Cryogens	Inert/ Cryogens	Inert/ Cryogens	Inert/ Cryogens	Inert/ Cryogens	Inert/ Cryogens	Inert/ Cryogens	Inert/ Cryogens	Ine Cry
3,298	3,298	3,298	3,298	3,298	3,298	3,298	3,298	3,298	3,2
		5,283/ 38,128	5,497/ 38,781	3,946/ 37,003	3,946/ 37,003	3,946/ 37,003	4,763/ 36,673	4,733/ 37,003	2 2
5,983 39,858	6,123/ 40,172			877/ 737	1,601/ 828	2,129/ 2,777	2,129/ 2,777	2,129/ 2,777	3 1
		574/ 1,675	574/ 1,675	574/ 1,675	574/ 1,675				
9,281/ 39,858	9,421/ 40,172	9,155/ 39,803	9,369/ 40,456	8,695/ 39,415	9,419/ 39,506	9,373/ 39,780	10,190/ 39,450	10,160/ 39,780	8,8 40,
396	422	451	477	679	622	608	634	608	433

iponents.

3

FOLDOUT FRAME [redacted]

3-51

ITS AND COMPONENTS

IVb	IVc	Va	Vb	VIa	VIb	VII	VIII	Ref
Inert/ Cryogens	Inert/ Cryogens	Inert/ Cryogens	Inert/ Cyrogens	Inert/ Cryogens	Inert/ Cryogens	Inert/ Cryogens	Inert/ Cryogens	Inert/ Cryogens
3,298	3,298	3,298	3,298	3,298	3,298	3,298	3,298	3,731
		2,084/ 29,143	2,126/ 29,022	2,084/ 29,143	2,084/ 29,143	2,128 29,022	2,084/ 29,143	2,021/ 29,129
4,763/ 36,673	4,733/ 37,003					3,410/ 8.994	6,468/ 9,547	2,763/ 8,191
								877/ 737
2,129/ 2,777	2,129/ 2,777	3,472/ 11,406	3,450 10,950	7,323/ 11,892	5,287/ 11,892			481/ 1,646
						574/ 1,675	574/ 1,675	63/51
10,190/ 39,450	10,160/ 39,780	8,854/ 40,549	8,878/ 39,972	12,705/ 41,035	10,669/ 41,035	9,410/ 39,691	12,424/ 40,365	9,936/ 39,754
634	608	433	443	431	484	519	488	774

FOLDOUT FRAME 1

Table 10.3-52
INTEGRATED SYSTEMS COMPARISON

FOLDOUT FRAME 2

Parameter \ System	Ia	Ib	Ic	IIa	IIb	IIIa	IIIb	IVa	IVb	IVc	Va	Vb	VIa	VIb	VII	VIII
Cryogens Use Flexibility	Good	Good	Fair	Fair	Fair	Fair	Fair	Fair	Fair	Fair	Fair	Fair	Fair	Fair	Poor	Poor
Insulation or Thermal Protection																
• Reusability • Operational Simplicity	Good	Good	Poor	Good	Poor	Fair	Fair	Fair	Fair	Good	Fair	Fair	Fair	Fair	Fair	Fair
Acquisition Requirements	Very Stringent	Very Stringent	Stringent	Stringent	Stringent	Moderate	Moderate	Moderate	Moderate	Moderate	Stringent	Stringent	Easy	Moderate	Moderate	Very Easy
Helium Use Requirements	Large	Large	Medium	Large	Large	Large	Large	Medium	Medium	Medium	Medium	Large	Small	Medium	Medium	Small
Adaptation to Alternate Operating Modes	Poor	Poor	Poor	Medium	Medium	Medium	Medium	Medium	Medium	Medium	Medium	Medium	Medium	Medium	Good	Good
System Complexity																
• Diversity of Component Type	Few	Few+	Few+	Moderate	Moderate	Many	Many	Many	Many	Many	Moderate	Moderate	Moderate	Many	Many	Many
• Tanks – Number	Few	Few	Few+	Few+	Few+	Many	Many	Moderate	Many	Moderate	Moderate	Moderate	Moderate	Many	Many	Many
– Size – Configuration	Large Moderate Complex	Large Moderate Complex	Large Complex	Large Moderate Complex	Large Complex	Large Moderate Complex	Large Moderate Complex	Medium Moderate Complex	Medium Complex	Medium Moderate Complex	Medium Moderate Complex	Medium Moderate Complex	Medium Simple	Medium Complex	Small Simple	Small Simple
• Control	Moderate	Moderate	Moderately Stringent	Moderate	Moderately Stringent	Moderately Simple	Moderately Simple	Moderately Stringent	Stringent	Moderately Stringent	Moderately Stringent	Moderately Stringent	Stringent	Stringent	Simple	Moderately Simple
• Functional Requirements																
Operational Characteristics																
• Loading	Simple	Simple	Moderate	Moderate	Moderately Complex	Moderately Complex	Moderate	Moderate	Moderately Complex	Moderate	Moderate	Moderate	Moderate	Moderately Complex	Complex	Complex
• Atmospheric Operation	Simple	Simple	Moderately Complex	Simple	Moderately Complex	Simple	Simple	Simple	Simple	Very Simple	Moderately Complex	Moderately Complex	Moderately Complex	Moderately Complex	Simple	Simple
• Maintenance																
• Post-Flight Activity	Medium	Medium	Medium	Medium	Medium	Medium	Medium	Medium	Medium	Medium	Little	Little	Little	Medium	Medium	Little
Safety																
• Inerting	Impose	Impose	Impose	Impose	Impose	Of Large Tanks	Of Large Tanks	Of Large Tanks	Of Large Tanks	Of Large Tanks	Of Large Tanks	Of Large Tanks	Of Large Tanks	Of Large Tanks	Of Large Tanks	Of Large Tanks
• Leakage (In Atmosphere)	Small	Small	Medium	Medium	Medium Large	Medium Large	Large	Large	Medium Large	Medium Large	Medium Large	Medium Large	Medium Large	Large	Large	Large
• Pressure Level	Medium	High														
Push the Technology?	Yes	Yes	Yes	Yes	Yes	Very	Very	Very	Very	Very	Little	Little	Yes	Very	Little	Yes
Development Risk	Medium+	Medium+	Medium+	Medium	Medium+	Medium+	Medium+	Medium+	Medium	Medium	Medium	Medium	Medium	Medium+	Little	Little

10.4 INTEGRATED SYSTEM TRADEOFF STUDIES

In reviewing the weights and number of components for each integrated system shown in Table 10.3-51, it can be seen that most of the integrated systems weigh less than the reference nonintegrated system and all integrated systems have fewer components. In arriving at the weights, an OIPS was employed that utilized a warm gas prepressurization system. The gas was assumed to be stored in high-pressure tanks at ambient temperatures. When the prepressurization is supplied from the ACPS accumulators, a significant weight in the OIPS can be saved. If the OIPS tanks are prepressurized on the ground or allowed to self-pressurize, this savings would be unavailable and could not be attributed to a weight reduction for integration purposes. The relative change between the integrated system and the nonintegrated system would be 324 lb - i.e., the reference system would be reduced by 433 lb, and the integrated system would be reduced by 109 lb.

With this situation and including the cryogen weights, eight integrated systems are lighter than the reference system. These are systems Ia, Ib, IIa, IIIa, IIIb, IVa, Vb and VII. The lightest system is IIIa and the system with the lowest inert weight is Ia. The system with the fewest components is Ia. There are seven systems with fewer than 451 components (an arbitrary choice for the sake of discussion). If one were to select systems strictly on the basis of weight and number of components, then Ia, Ib, IIa, IIIa, IIIb, and Vb appear to be good. However, since Systems Ic and IVc are closest to the MCD and NAR Phase B configurations, respectively, they are included in further discussion and comparisons.

Each of the above systems is discussed by group, and a rationale is developed for eliminating some of them.

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10.4.1 Systems Ia, Ib, and Ic

Systems Ia, Ib, and Ic are all completely integrated in that the cryogens are stored in common tanks and conditioned oxygen and hydrogen are stored in accumulators for use with all systems except OMPS. The only difference between Systems Ia and Ib is that a new 8,000- to 10,000-lb thruster is required for the OMPS in System Ia, whereas RL-10 engines are used for System Ib. Both systems employ an acquisition device that is enclosed by a bulkhead having screened ports. The entire tank is pressurized with cold helium and the tanks are vacuum-jacketed. The overall weight of System Ia is considerably less than System Ib, so there is a strong tendency to choose the lighter system that would employ the new thrusters. The pumps have to be developed anyway; therefore, it is only the thruster that requires additional development. The final selection must be based on cost considerations. No doubt it will cost more for a thruster development than it would to employ the RL-10; however, the cost difference may not be as great as may be imagined when the overall vehicle weight and payload penalties are factored in.

System Ic utilizes start tanks placed within the OMPS oxygen and hydrogen tanks and does not employ vacuum jackets. The start tanks serve to provide a more definitive arrangement from the acquisition point of view. However, the same broad range of requirements is placed on the acquisition devices for all Group I systems. The start tank tends to be heavy and imposes a weight penalty that is commensurate with having a vacuum jacket on the tanks while not having the advantage of operational simplicity made available by the use of vacuum jackets. The quantity of helium used is less for the start tank than for System Ia; however, each time that the start tank is refilled the helium must be vented overboard. In System Ia, the helium is maintained in the tank and can be recovered during subsequent refill operations. The start tank arrangement tends to place duty-cycle limitations on the system because the refill is required during OMPS burns,

and the start tank size, transfer line size, and operating pressures are dependent upon refill time, acceleration, and quantity. Thus, System Ia would appear to be the best system to select within this group.

10.4.2 System IIa

System IIa is different from Ia in that the fuel cell and life-support cryogens are stored separately in supercritical tanks. This permits these cryogens to be conditioned by the vehicle-waste heat and, thereby, obtain some savings in conditioning fluids. Generally speaking, all other problems contained in System Ia are also contained in System IIa. Therefore, there is no strong reason for selecting System IIa over Ia.

10.4.3 Systems IIIa and IIIb

System III provides an approach to easing the requirements imposed on the acquisition devices by separating the APU reactants and placing them in a separate set of vacuum-jacketed tanks. System IIIa employs subcritically stored APU reactants, and System IIIb employs supercritically stored reactants; otherwise the two systems are the same. By not having the fuel cell and APU reactants stored in the OMPS and ACPS tanks, vacuum jackets are no longer necessary on the large tanks; therefore, the system weights are relatively low. System IIIa is lighter than IIIb, because the APU reactant is stored subcritically. This presents some problems in that acquisition devices are needed. However, the operational profile is such that the requirements are not stringent. The zero-g acquisition takes place when the tanks are nearly full, so the reactants can be easily acquired. As the reactants are being depleted, they are under a 1-g acceleration, and the depletion problem is simplified. In System IIIa, the APU reactants are stored supercritically and high-flow heat exchangers are required to maintain the tank pressure during expulsion. This presents some problems in heat exchanger design and controlability. All in all, there would be a tendency to select System IIIa.

10.4.4 System IVc

System IVc is similar to the NAR Phase B system. This system is heavy, primarily because of the combination of using vacuum jackets on the large OMPS tanks and utilizing vacuum-jacketed supercritical tanks for the APU, FC, and life-support cryogens. However, the acquisition problem is somewhat alleviated by utilization of the supercritically stored APU and fuel cell cryogens; although zero-g acquisition is still required for the ACPS feed system. There would be a tendency not to select this system, primarily because it is heavy.

10.4.5 System Vb

There would be a tendency to eliminate Vb on the basis that the system embodies most of the problems that the other systems have, yet lacks the versatility of OMPS-ACPS propellant-use interchangeability. The advantage lies in the fact that the vacuum jackets are not as heavy for the smaller ACPS, APU, FC, EC/LSS tanks as for the larger completely integrated systems. Acquisition devices are not complicated by the fact that they have to operate in large tanks as in other systems such as the System I group.

10.4.6 Summary

In summary, two systems seem to have advantages: Systems Ia and IIIa. These systems are tentatively selected as reference systems, and detail schematics have been prepared.

10.4.6.1 System Ia. Figure 10.4-1 shows a schematic of System Ia. The integration mode employed is to store the OMPS, ACPS, APU, fuel cell, and EC/LSS cryogens in common subcritical storage vessels. Common pumps are used to feed liquid to the OMPS engine and, during nonoperation periods of the OMPS, to feed heat exchangers for storing gas in 2,000 psi accumulators.

The combination employed is for the single-tank configuration with the pump at-the-tank and helium prepressurization and pressurization. Optimum line diameters and tank pressures are those used for the subsystem studies.

For the integration mode studied here, it is necessary to have three pump sets to meet the ACPS fail-operational/fail-safe criteria. Three 8,000-lb thrusters were used for the initial sizing done earlier, and these were retained for the current updating. Therefore, there is a better chance of meeting the fail-operational/fail-safe criteria on the OMPS system for the three-thruster integrated case than for the case where two RL-10 engines are employed. A higher I_{sp} of 456 sec at the thruster can be used. Since the integrated turbopump systems must operate on conditioned gas from the ACPS accumulators, some additional losses are experienced as compared to the turbopump operated at the engine from an expander cycle or its own cold fluid-fed gas generator.

The integrated portion of the ACPS system employs the same basic features as the subcritical stored nonintegrated ACPS. A high-pressure accumulator (2,000 psi) is employed, and the gases are conditioned to 250^{o}R for H_2 and 380^{o}R for O_2. The 380^{o}R is about the minimum temperature for storage at high pressures, if two-phase flow is to be avoided after blowdown and regulator throttling.

For the integration mode, where a common set of pumps is used to supply liquid to the OMPS thrusters and alternately feed heat exchangers for ACPS operation, several minor problems exist. Among these problems are: lower efficiency due to variable operating conditions, turbine's use of conditioned gases from the accumulators, more on-off cycles due to mismatch between OMPS and ACPS flow rates, and the requirement for simultaneous liquid flow to the OMPS and ACPS heat exchangers.

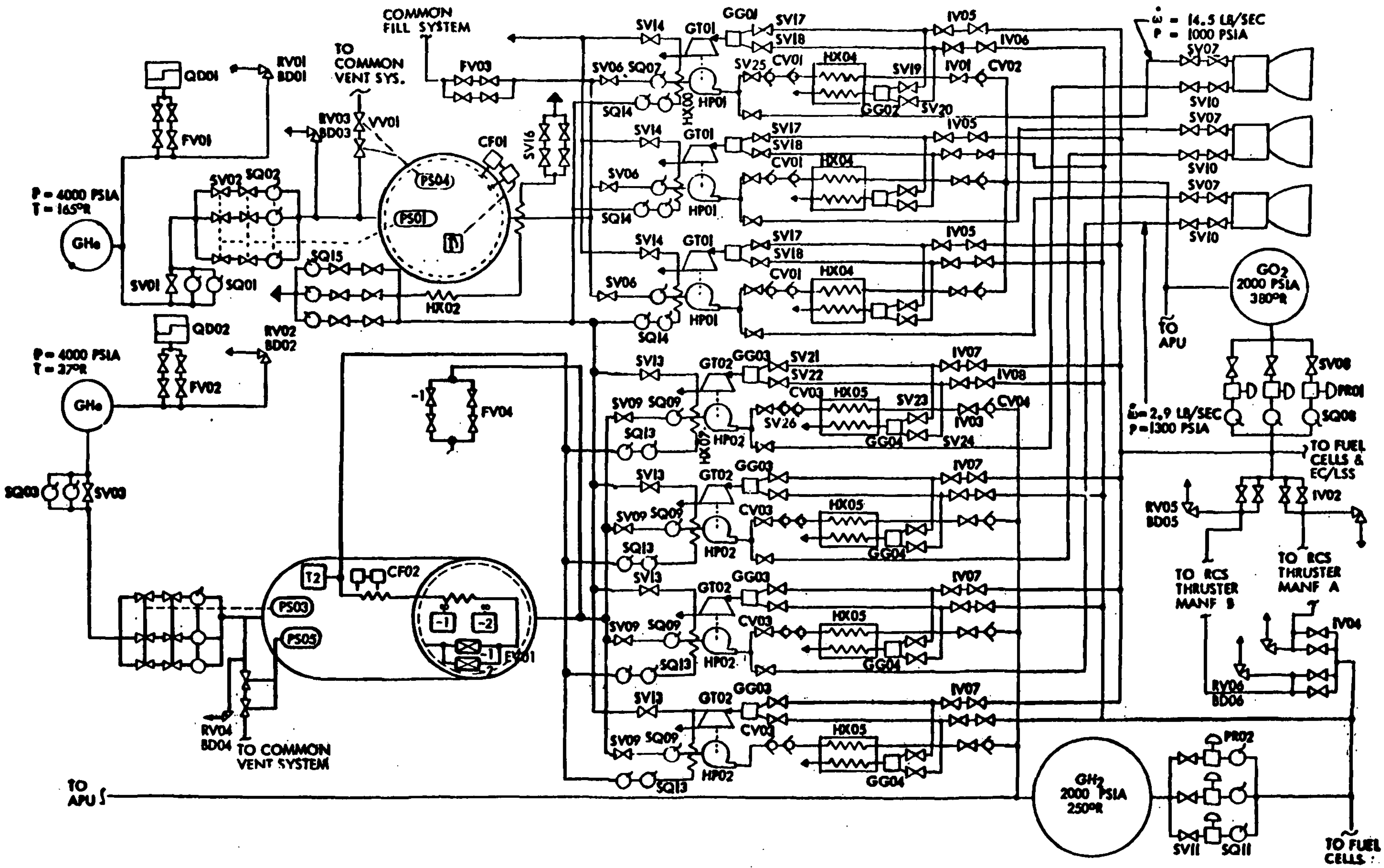

Fig. 10.4-1 Integrated OMPS/ACPS/APU/FC/EC/LSS With Common Pumps

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This latter problem results from having too little gas in the accumulator to feed the turbopumps during a long OMPS burn. There are several possible solutions as follows:

a. One potential solution is to use larger accumulators; however, this results in a significant weight penalty.

b. Another approach is to add a fourth pump and heat exchanger set with the associated redundant valves and control. This would result in having to use two pumps at a time; therefore, four would be required to meet the fail-operational/fail-safe criteria.

c. A third approach is to have only a three pump set and utilize an alternate pump when accumulator recharge is necessary. With this operation mode, two pump failures would cause the OMPS deorbit burn to be performed intermittently. When the accumulators become depleted, the OMPS would have to shut down for approximately 10 sec. This means that two or three shutdowns would be required, which might cause some operational problems for deorbit and reentry control.

d. A fourth approach would be to oversize the pump and add additional exchangers designed to operate at low flowrates. This approach adds complexity that is more extensive than adding a pump set.

Of the approaches mentioned, the addition of a pump set (item b.) seems most appropriate.

Fuel-cell reactants and life-support oxygen are taken from the regulated side of the accumulators. The cool reactants can be passed through heat exchangers in the fuel cell module and, thereby, help reduce the cooling load within the module. The life-support oxygen would be further conditioned by cabin heat exchangers that can be relatively small.

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The APU reactants are taken from the high-pressure side of the accumulator. They are supplied to regulators which regulate to approximately 600 psia. This is a higher pressure than the rest of the system, because better specific reactant consumption can be obtained.

10.4.6.2 System IIIa. System IIIa is represented by three schematics shown in Figs. 10.4-2, -3, and -4. The OMPS and ACPS propellants are stored in common subcritical tanks. Common pumps are used and the system is very similar to System Ia, except vacuum jackets are not required. The acquisition system need only to operate in the low-gravity environment of space flight rather than the combination of low gravity and high gravity of reentry and atmospheric flight.

The APU system is completely separate from the other systems because of the unique operating conditions and rather limited operating time. Reactants are stored in separate subcritical vacuum-jacketed tanks. Pumps are employed to raise the pressure to 1,360 psi. Borske type pumps are employed that have the characteristic of a relatively flat pressure-flowrate curve at the low flowrates. Acquisition devices are required for start in space, but the tanks are relatively small and can be depleted in an efficient manner during the atmospheric portion of the flight.

The fuel cell reactants and life-support oxygen are stored in supercritical vacuum-jacketed tanks. Flowrates are relatively low and, therefore, the problem of supplying heat to the tanks to maintain tank pressure is not too difficult. The Freon-21 coolant loop can be utilized for this function.

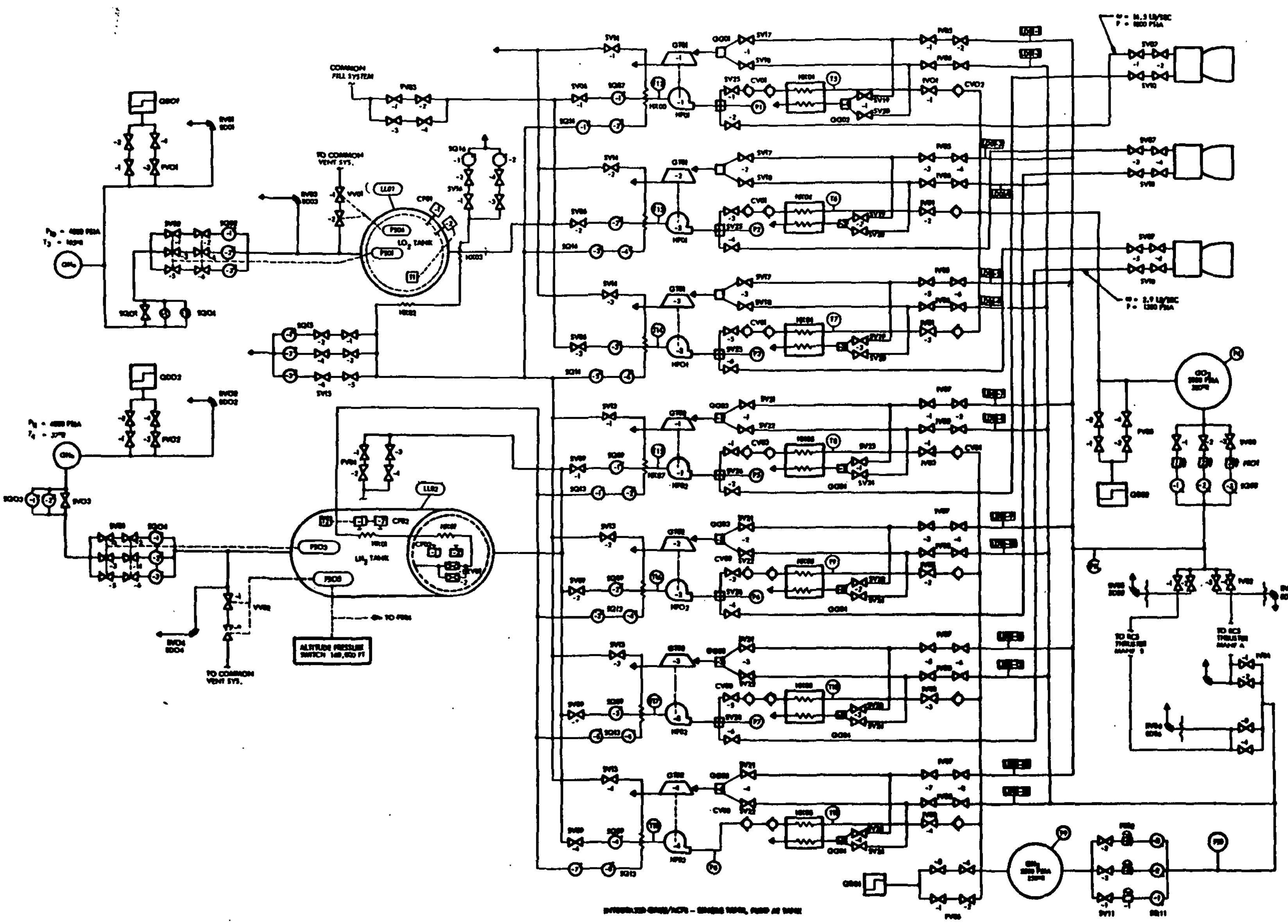

Fig. 10.4-2 OMPS/ACPS with Pump-At-Tank

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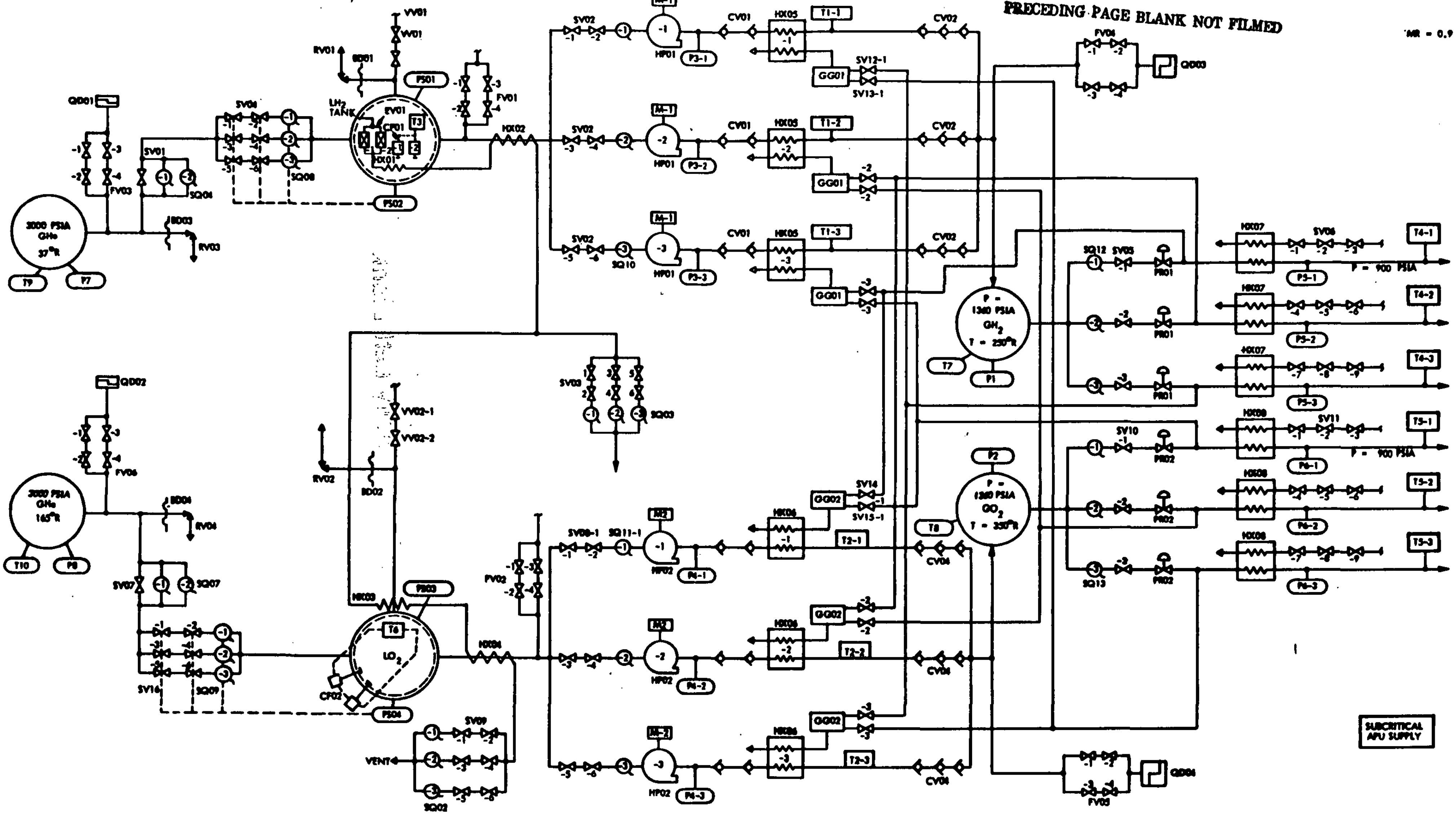

Fig. 10.4-3 Subcritical APU Cryogenic Supply Subsystem

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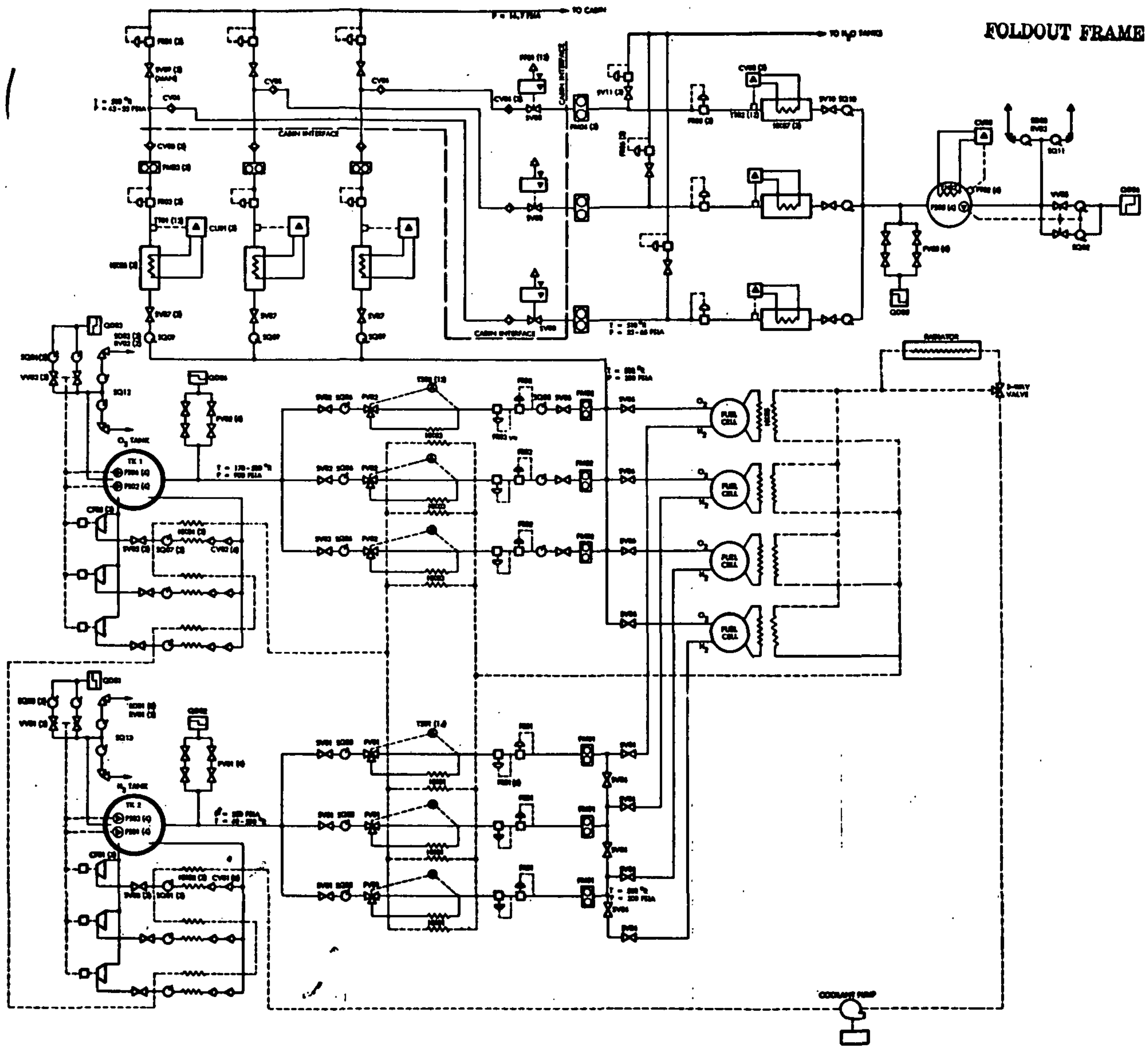

Fig. 10.4-4 Integrated Supercritical Fuel Cell/Life Support Subsystem

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10.5 SUPPLEMENTAL APPENDIX - DETAIL STUDIES APPLICABLE TO INTEGRATED SYSTEMS

Detail studies on specific ways of integrating certain functions within each subsystem were conducted throughout the overall study effort. These studies are quite varied in their basic nature and application and, therefore, will be discussed separately. The items covered are:

- Prepressurization of the OIPS and the OMPS with conditioned gases from the ACPS accumulators
- Utilization of the ascent tanks residuals and propellants as heat sinks for the vehicle waste heat (from liftoff to radiator deployment)
- Utilization of propellants to absorb vehicle waste (also provides some conditioning)
- Description of procedures to refill supercritical ACPS propellant tanks from subcritical OMPS propellant tanks
- Analyses and arrangement of start tanks

10.5.1 Prepressurization of OIPS and OMPS from ACPS Accumulators

10.5.1.1 <u>OIPS Prepressurization</u>. The integration mode between the ACPS and the OIPS is prepressurization of the OIPS tanks with conditioned GO_2 and GH_2 from the ACPS accumulator. Changes that result to the OIPS are shown in Table 10.5-1. A greater amount of prepressurant gas is required when it is supplied from the ACPS accumulators than would be required if the prepressurant is supplied from ambient-stored OIPS prepressurant vessels, because the gas temperature in the accumulators is lower than it would be if it were withdrawn from the warm storage vessels. The differences in weight show that it is advantageous to use gases from the ACPS accumulators for prepressurization of the OIPS. It may be possible to permit the ascent tanks to self-pressurize, in which case a slightly greater weight savings would be realized.

Table 10.5-1

OIPS PREPRESSURANT CHANGES

REMOVED FROM OMPS (433 LB TOTAL)		COMPONENTS	NO.	WEIGHT
PREPRESSURANT (520°R ISOTHERM)		FV01	1	5.7
GO_2	5	RV01	2	13.5
GH_2	15	BD03	2	3.0
TANKS (4,000 PSIA)		SV02	1	5.2
		RV02	2	15.3
O_2	17	BD04	2	3.0
H_2	350		10	45.7 LB

ADDED TO ACPS (109 LB TOTAL)

PREPRESSURANT		CONDITIONING	STORAGE TANK ΔWEIGHT	LINE WEIGHT
GO_2 (350°R)	6.0	–	2.0	15.0
GH_2 (250°R)	23.0	8.0	40.0	15.0

10.5.1.2 OMPS Prepressurization. The integration mode between the ACPS and the OMPS is prepressurization of the OMPS tanks for each OMPS start. Resultant changes in components and weight are shown in Table 10.5-2. To prepressurize the OMPS with warm gases, it is necessary to make sure that an ullage space exists in the vicinity of the pressurant inlet; otherwise the pressurant would collapse in temperature and pressure, and large amounts of pressurant would be required. The gas weights shown in the table are based upon this assumption. One way to achieve this is to utilize the ACPS +X thrusters to provide acceleration for propellant orientation for the prepressurization period. If it is necessary to do this, a weight penalty must be assigned to any system utilizing the hot-gas prepressurization techniques. Approximately 460 lb of propellant is required for nine orientations. All of this weight can not be assigned as a penalty, because some weight provides useful ΔV, which the OMPS does not have. The penalty for conditioning is approximately 70 lb of cryogens. If an integrated subcritical OMPS-ACPS storage system is being considered, then the penalty is the 70 lb plus the tankage to store it of about 3 lb resulting in an overall penalty of 73 lb. If a supercritical ACPS system is used, the storage weight for the usable propellant increases to about 260 lb and the total penalty is 330 lb.

10.5.2 Utilization of Ascent Tank Residuals and Propellants

Orbital Injection Propellant Supply residuals can be used for cooling during ascent and the first two orbits, while the radiators are not deployed. The heat rates, a system cooling schematic, and a list of components are shown in Table 10.5-3. During the groundhold and ascent portions of the mission, a total heat of 7,680 Btu is generated; this can be easily absorbed by the H_2 cryogens with only a small increase in temperature and vapor pressure ($\Delta P = 0.15$ psi) resulting. After depletion of the OIPS propellants, the residuals can be heated and vented to absorb the heat generated during the next two orbits. Sufficient residuals are available for this function.

Table 10.5-2

OMPS PREPRESSURANT SYSTEM CHANGES

REMOVED FROM OMPS (965 LB TOTAL)

PREPRESSURANT ($520^{o}R$ ISOTHERM)

GO_2	359 LB
GH_2	3 LB

TANKS (4,000 TO 200 PSI)

O_2	435 LB
H_2	155 LB

COMPONENTS	NO.	WEIGHT
FV01	1	1.5
SQ01	1	0.75
QD01	1	1.75
RV01	1	1.92
BD01	1	0.2
QD02	1	2.0
SQ02	1	0.9
FV02	1	1.77
RV02	1	1.77
BD02	1	0.2
	10	12.8 LB

ADDED TO ACPS (541 LB TOTAL)

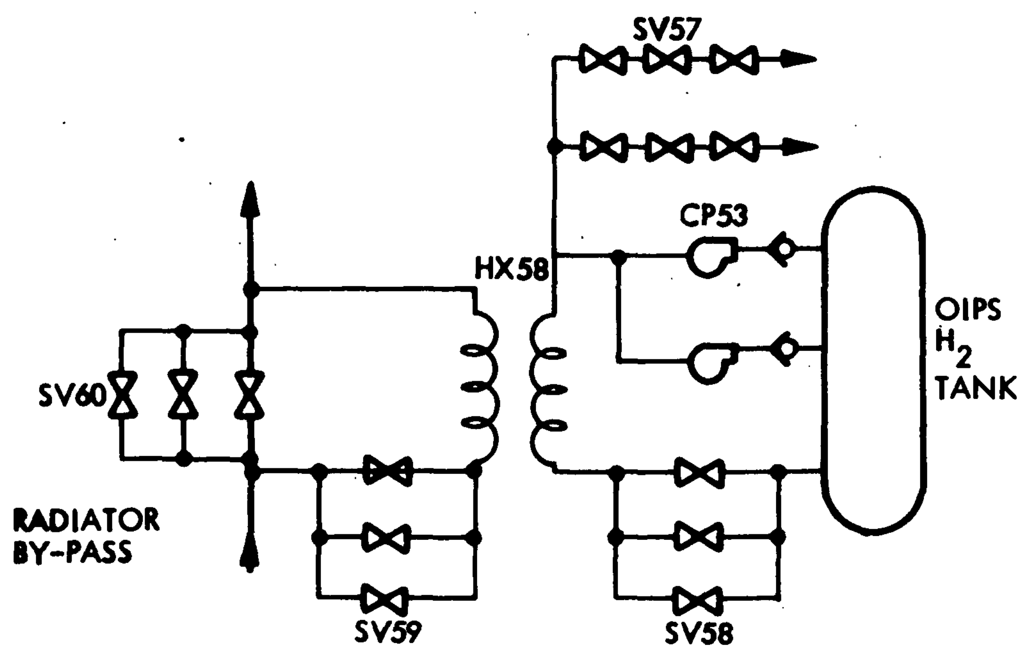
PREPRESSURANT		CONDITIONING	STORAGE TANK ΔWEIGHT
GO_2 ($350^{o}R$)	420	23	~61
GH_2 ($250^{o}R$)	6	2	~29

Table 10.5-3

HEAT GENERATION AND REJECTION – FIRST TWO ORBITS

PHASE	DURATION (HR)	CABIN AND CREW MIN. (BTU/HR)	CABIN AND CREW MAX. (BTU/HR)	ELECTRONIC MIN. (BTU/HR)	ELECTRONIC MAX. (BTU/HR)	TOTAL MIN. (BTU)	TOTAL MAX. (BTU)
PRELAUNCH	0.083	860	2,600	24,200	34,130	2,100	3,010
ASCENT	0.11	1,860	4,600	24,270	36,860	2,970	4,670
PHASING	3.0	0	3,600	19,440	43,680	58,100	142,000

7,680 BTU THROUGH ASCENT – NO VENTING $\Delta P = 0.15$



COMPONENT	NO.	WEIGHT
CP53	2	6
SV57	6	15
SV58	3	8
SV59	3	4
SV60	3	4
HX58	2	2
		39

10.5.3 Utilization of Vehicle Waste Heat

If the fuel cell system is integrated with the supercritical ACPS and is supplied with conditioned reactants from the accumulators, a heat-transfer system can be included as an additional integration mode. This prevents having to condition any more reactant than is absolutely necessary. A schematic of this system is shown in Fig. 10.5-1. For redundancy purposes, three parallel systems are assumed. Heat exchangers HX62 and HX61 transfer heat to the fluid flowing from the storage vessel to the accumulator, and heat exchangers HX55 and HX56 transfer heat to the O_2 and H_2 storage tanks. The added components to transfer the heat and the amounts of conditioning propellants saved are shown in Table 10.5-4. By incorporating this form of integration, a weight savings of approximately 73 lb can be realized.

The optimum storage pressure for the separate ACPS subsystems is 600 psi for the H_2 storage and less than 700 psia for the O_2 subsystem. However, since the O_2 system is operated supercritically, a minimum pressure of 850 psia is utilized. These studies were based on 1,000 and 4,000 lb of usable H_2 and O_2, respectively. To determine the validity of this trend with an integrated ACPS system, a storage system trade was conducted for a higher propellant loading of 8,095 lb for O_2 and 2,499 lb for H_2. Results presented in Fig. 10.5.2 show that the optimum storage pressure shifted very little. Therefore, the same storage and conditioning temperature and pressure conditions were maintained for the integration study as were employed for the separate subsystem definition.

10.5.4 Refill of Supercritical Tanks

One approach to integrating the various subsystems is to refill supercritical pressure vessels from subcritical storage tanks. This has the advantage of diminishing the potential problems associated with liquid acquisition, while not incurring the weight penalty associated with storing large propellant quantities in supercritical tanks.

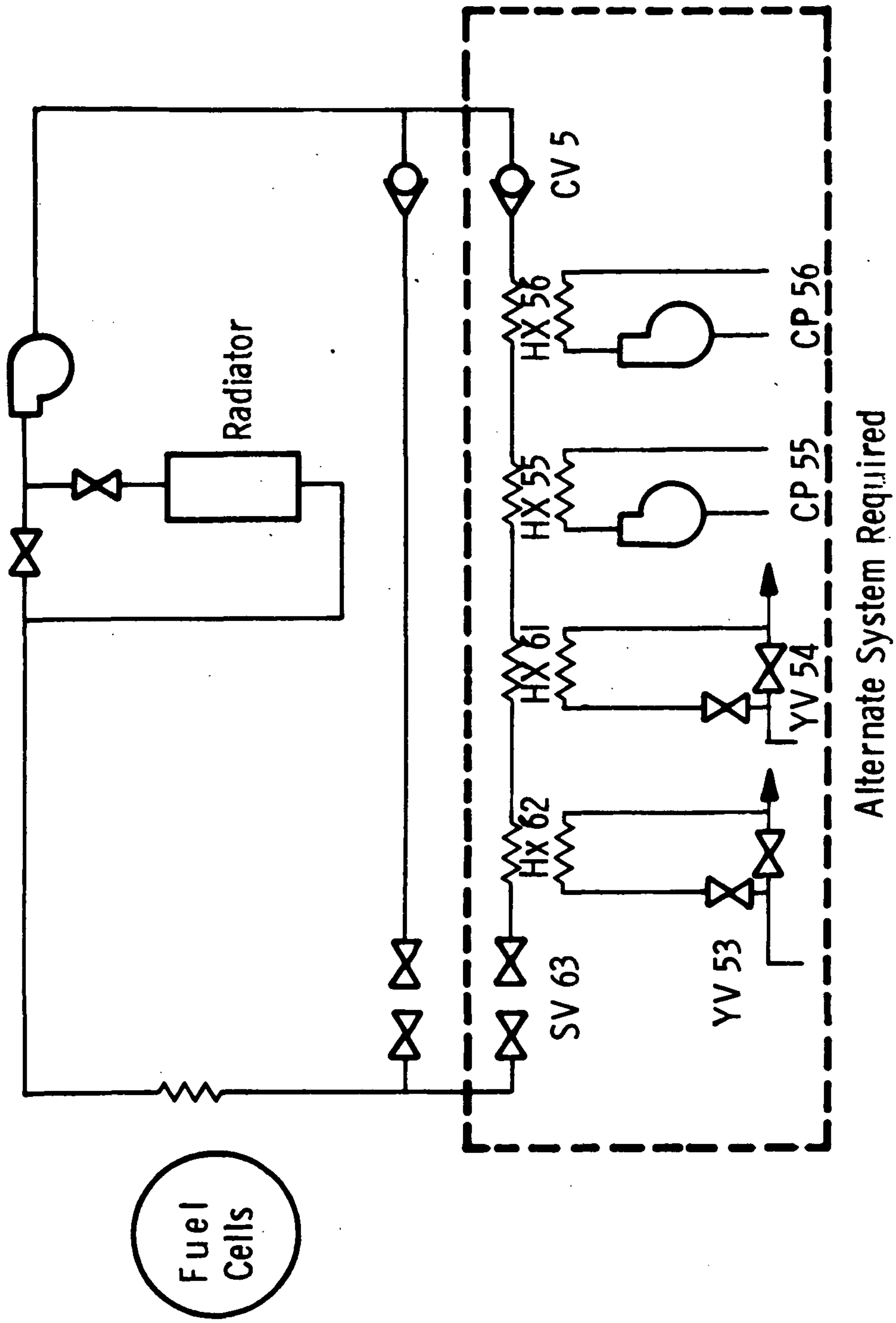


Fig. 10.5-1 Fuel Cell to Cryogens Heat Transfer System

Table 10.5-4

HEAT TRANSFER SYSTEM WEIGHTS

Components	Number	Weight
HX 61	2	0.8
HX 62	2	0.4
HX 55	2	1.0
HX 56	2	0.4
CP 56	2	4.0
CP 55	2	8.0
YV 53	4	12.0
YV 54	4	12.0
SV 63	6	18.0
CV 51	3	4.5
Total		61.0
Lines (Estimate)		10.0
		71.1

Conditioning required if fuel cell heat is not used to condition fuel cell reactant.

Condition	175 lb H_2 = 64 lb	144 lb
Condition	1,450 lb O_2 = 80 lb	

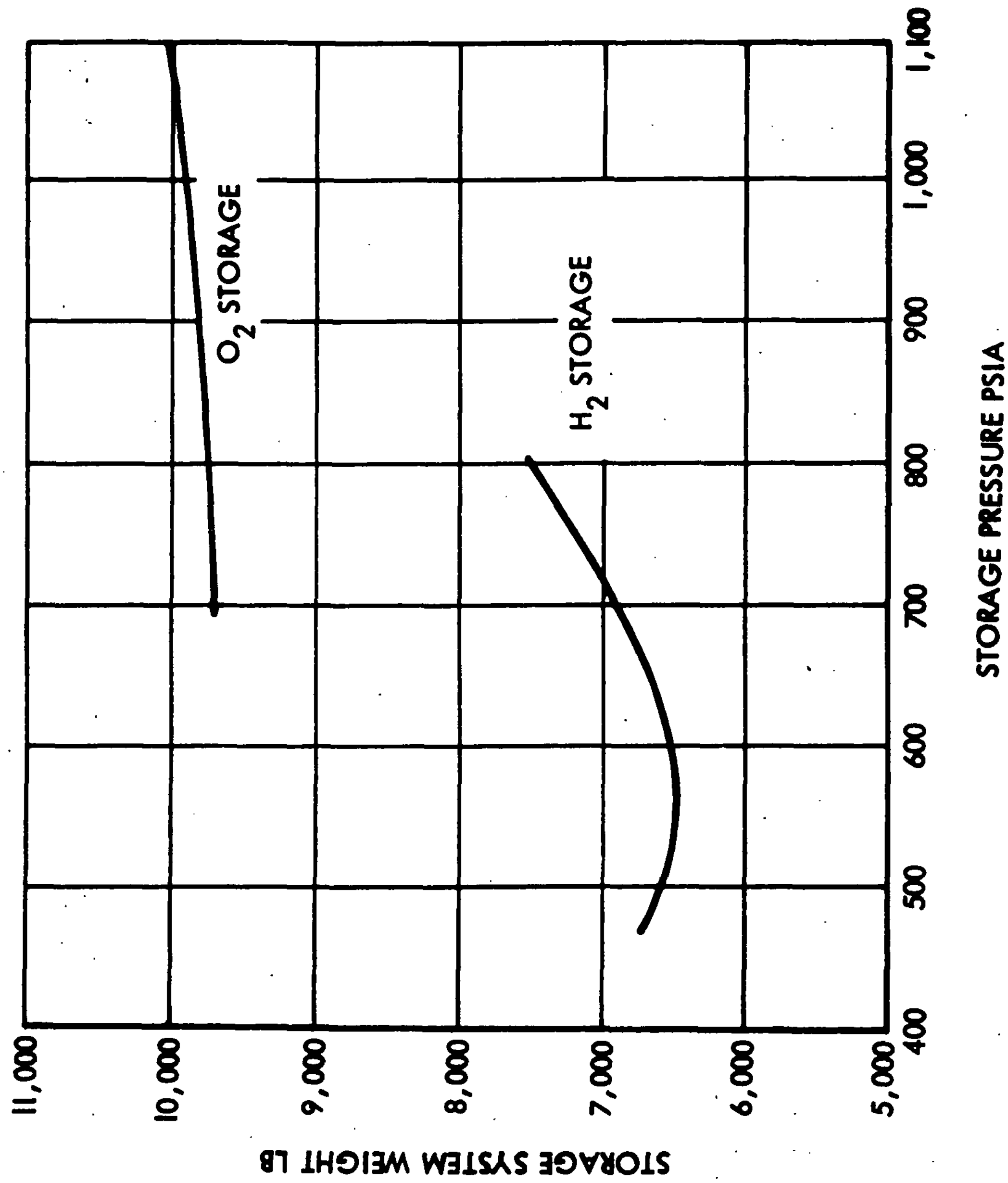


Fig. 10.5-2 Storage System Weights for Integrated Supercritical Tanks

However, there are problems with the compatibility of pump output and mission profile (e.g., see Table 10.5-5). Three modes of transfer with pumps come to mind as indicated in this table. If the RL-10 is considered, it is immediately observed that the O_2 pressure output is not compatible with the O_2 tank pressures. Nevertheless, the O_2 tank could be vented to a lower pressure and refilled with the high-pressure liquid out of the O_2 pumps. This would cause oxygen weight loss each time of refill and also cause the O_2 to be subcritical during the transfer process.

Table 10.5-5
REFILL SUPERCRITICAL TANKS

Refill with RL-10 Pumps

- Pump Pressures O_2 540, H_2 972 Psi
- Tank Pressures O_2 800, H_2 450 Psi
- Limited Refill Time

Refill with New OMPS Engine Pumps

- Pump Pressures, O_2 1000 Psia, H_2 1300 Psia
  O_2 800 Psia, H_2 450 Psia
- Limited Refill Time

Refill with Special Refill Pumps

- Fluid Orientation Required

Another problem exists with establishing how much flow can be tapped off the pump without interference with satisfactory engine operation. It is expected that a maximum flow variation of 10 percent should not be exceeded.

Another approach is to design the capability of flow tapoff into the pump and engine system, if a new OMPS engine development is initiated. Among the problems are that refill time and quantity are limited to periods of OMPS operation.

A third approach is to dedicate a special transfer pump to the system and refill the tank at a lower flowrate. However, this requires that the liquid be pumped during periods of adverse acceleration, and an acquisition device is needed.

Some of the problems of duty-cycle compatibility, pump sizing, refill time, and fluid characteristics in the supercritical tanks during transfer are presented. To illustrate the duty-cycle compatibility problem and the inability to refill during OMPS operation, reference is made to Table 10.5-6; these data are extracted from the duty cycles presented in the Requirements Sections of the Propellant Supply Systems Task Report. The table presents data on the cryogens used at certain major intervals for a five-burn OMPS mission.

Using the Table 10.5-6 data and computing the amounts of cryogens that can be resupplied to the storage tanks under the conditions indicated in the table, the data in Table 10.5-7 result. Shown in the latter table for each subsystem are (1) the total amounts of cryogens consumed, (2) the quantity that can be resupplied from the OMPS pumps at 10 percent of the flowrate, and (3) the minimum storage tank capability that is permissible. The figures in the last column represent the minimum amounts of cryogens for which the tanks must be sized. Also shown is the percentage of the total usable.

Table 10.5-6

CRYOGENS UTILIZATION COMPARISON FOR REFILL

EVENT	MISSION TIME (hr)	OMPS BURN TIME(1) Max/Min (sec)	POTENTIAL FOR TRANSFER FROM OMPS (2) Max/Min		CRYOGENS CONSUMED (CUM) Max/Min					
					ACPS(3)		APU(4)		FUEL CELL	
			O_2(lb)	H_2(lb)	O_2(lb)	H_2(lb)	O_2(lb)	H_2(lb)	O_2(lb)	H_2(lb)
Phasing	0.83	206/173	591/493	118/99	67/67	21/21	70	78	25/11	3.0/1.4
Height Adjustment	1.58	160/135	460/383	92/77	75/75	24/24	70	78	32/12	4 /1.5
Coelliptic	2.37	15/12	46/33	9/7	77/77	25/25	70	78	30/13	5/1.6
TPI	3.85	12/10	33/30	7/6	650/234	201/73	70	78	35/15	7/1.8
Deorbit	166.63	280/234	800/700	160/140	3440/1460	1070/460	74	83	1430/725	172/90
Entry					4400/1900	1370/590	201	224	1442/728	174/90
Landing							408	454	1450/730	175/91

(1) At thrust = 15K lb and I_{sp} = 439 sec

(2) Assume 10 percent of flow to OMPS engine

(3) Assume mixture ratio = 4:1 at thrusters (3.2 overall)

(4) Assumes 283 HP hrs at MR = 0.9, cg pressure = 300 psi

Table 10.5-7

RESUPPLY QUANTITIES

SUBSYSTEM	CRYOGEN USED Max/Min		RESUPPLY QUANTITY Max/Min		MIN. STORAGE QUANTITY	
	O_2(lb)	H_2(lb)	O_2(lb)	H_2(lb)	O_2(lb)	H_2(lb)
ACPS	4400/1900	1370/590	910/807	212/171	3530/1253	1039/429
Percent	-	-	-	-	80/66	76/73
APU	408	454	74	83	338	376
Percent	-	-	-	-	83	84
FUEL CELL	1450/730	175/91	855/715	167/92	1375/710	165/88
Percent	-	-	-	-	95/97	95/97

Resupply from OMPS at 10 percent of thruster flowrate with thrust = 15K lb and I_{sp} = 439 sec

Due to the fact that the subsystems must operate during times when cryogens can not be transferred, the tanks must be sized to contain the cryogens required. Although a reasonably large portion of the usable cryogen required for the ACPS and fuel cell can be transferred, no real tank savings can be realized because of the long time periods when transfer is not possible.

The same type of information is presented in Table 10.5-8 for the cases where the subsystems are integrated. In the lower part of the table, the minimum storage quantity is shown. A small advantage is gained for the case where APU + FC cryogens are stored together. Savings in tank size can be realized in that the tank would have to be configured to contain only 75 percent of its full-use requirement for the O_2 tank and 60 percent for the H_2 tank.

From these results, note that to refill from a pump system that operates only when the OMPS engine is operating holds little advantage. Even if a separate pump is used that can pump at high flowrates, little advantage is gained if it can transfer cryogens only at time when the OMPS is operating.

Another method is to utilize a separate pump that can transfer at any time. This is dependent upon either (1) settling the liquids in OMPS propellant tanks by an induced-acceleration, or (2) installing a propellant acquisition device. The first approach introduces mission-operation restrictions and limitations; the second reestablishes the potential problem of acquisition, which the use of supercritical propellant storage has been trying to eliminate in the first place.

However, to examine whether or not transfer is attractive, it has been assumed that transfer can be made at any time by the utilization of an acquisition device. Under this assumption, a different set of limitations on propellant transfer results than have been described in the previous tables. It was assumed that no transfer could be made after 167.6 hours into the mission, which corresponds to the approximate time of initial reentry aerodynamic forces. This may not be a valid restriction; however, it seemed desirable

Table 10.5-8

CRYOGENS UTILIZATION - INTEGRATED SYSTEMS

EVENT	MISSION TIME (hr)	OMPS(1) BURN TIME Max/Min (sec)	POTENTIAL FOR TRANSFER FROM OMPS (2) Max/Min		(3) ACPS + APU + FC Max/Min		APU + FC Max/Min	
			O_2(lb)	H_2(lb)	O_2(lb)	H_2(lb)	O_2(lb)	H_2(lb)
Phasing	0.83	206/173	591/493	118/99	162/148	102/100	95/81	81/79
Height Adjustment	1.58	160/135	460/383	92/77	177/157	106/104	102/82	82/79
Coelliptic	2.37	15/12	46/33	9/7	187/160	108/105	110/83	83/80
TPI	3.85	12/10	33/30	7/6	775/319	286/153	125/85	85/80
Deorbit	166.63	280/234	800/700	160/140	4944/2259	1325/633	1504/799	255/173
Entry					6043/2829	1768/904	1643/929	398/314
Landing					6258/3038	1999/1135	1858/1138	629/545
		MIN. STORAGE QUANTITY			5143/2148	1723/890	1379/684	374/372
		PERCENT			82/71	87/78	75/60	60/68

(1) At thrust = 15 K lb and I_{sp} = 439 sec

(2) Assume 10% of flow to OMPS engine

(3) Assume misture ratio = 4:10 at thrusters (3.2 overall)

that all systems should be charged and ready to go before the high activity reentry portion of the mission begins. The amounts of cryogens used after this time along with the percent of total are shown in Table 10.5-9.

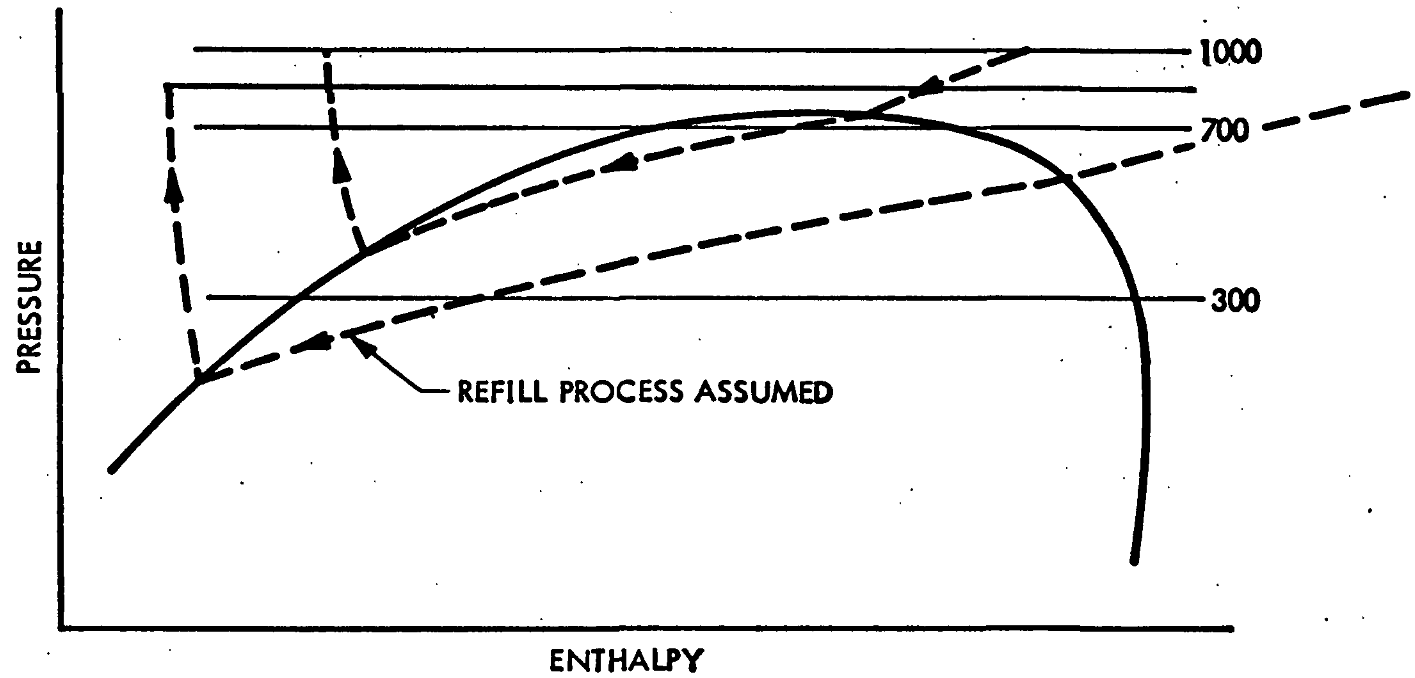
It can be seen from these values that significant gains in tank storage weight can be achieved if resupply can be achieved with these low-storage quantities. With this information in mind, the transfer problem was examined. An updated set of cryogen weights was used for this evaluation. The new weights were based on the same nominal values that the subsystems were based on. The total amount of reactants stored for operation of an integrated supercritical ACPS + APU + FC after retroburn is 1,792 lb of O_2 and 914 lb of H_2. This includes usable, conditioning, and residuals. The amount that can be refilled depends upon the refill processes, and usually a fraction of the total tank capacity can be refilled. To establish this amount, an examination of the refill process is in order.

To refill the supercritical tanks, it was assumed that high-pressure low-temperature fluids are transferred. For the O_2 tanks, the inlet and outlet conditions were assumed to be 175°R, 30 psia, and 182°R, 1,000 psia, respectively; and for H_2 about 39°R, 25 psia, and 49°R, 600 psia, respectively. For O_2 refill, the injection of the low-energy fluid into the nearly empty tank causes the fluid to be two phase; this is illustrated by Fig. 10.5-3. Two processes are shown: one for initial and final pressures at 1,000 psia and the one used in this trade study where the initial and final pressures are 850 psia. The initial condition, the replenishing fluid state, and the refill density are shown in the figure. For refill of the hydrogen tank, the process is assumed to begin at a pressure of 550 psia and, during the process, the minimum pressure is 500 psia and the fluid is always single phase. This is illustrated in Fig. 10.5-4, which shows the process overlaid on a hydrogen T-S diagram. The initial conditions at refill are assumed to be 550 psi and 170°R. It is necessary to permit the storage pressure to drop slightly from the operational value of 600 psi to assure that the tank does not overpressurize during the initial phase of the fill process. The final conditions

Table 10.5-9

CRYOGENS REQUIRED AFTER RETROBURN

ACPS + APU + FC Max/Min		APU + FC Max/Min	
O_2(lb)	H_2(lb)	O_2(lb)	H_2(lb)
1314/779	674/502	354/339	374/372
O_2(%)	H_2(%)	O_2(%)	H_2(%)
21/35	34/44	18/30	60/68



INITIAL CONDITIONS:
86% DEPLETED
P = 850 PSIA
T = 350°R
ρ = 9.2 LB/FT^3

REPLENISH WITH:
P = 900 PSIA
T = 182°R

ρ_f = 61 LB/FT^3
90% REFILL FRACTION

Fig. 10.5-3 Thermodynamic State of Cryogen Refill Supercritical Tank

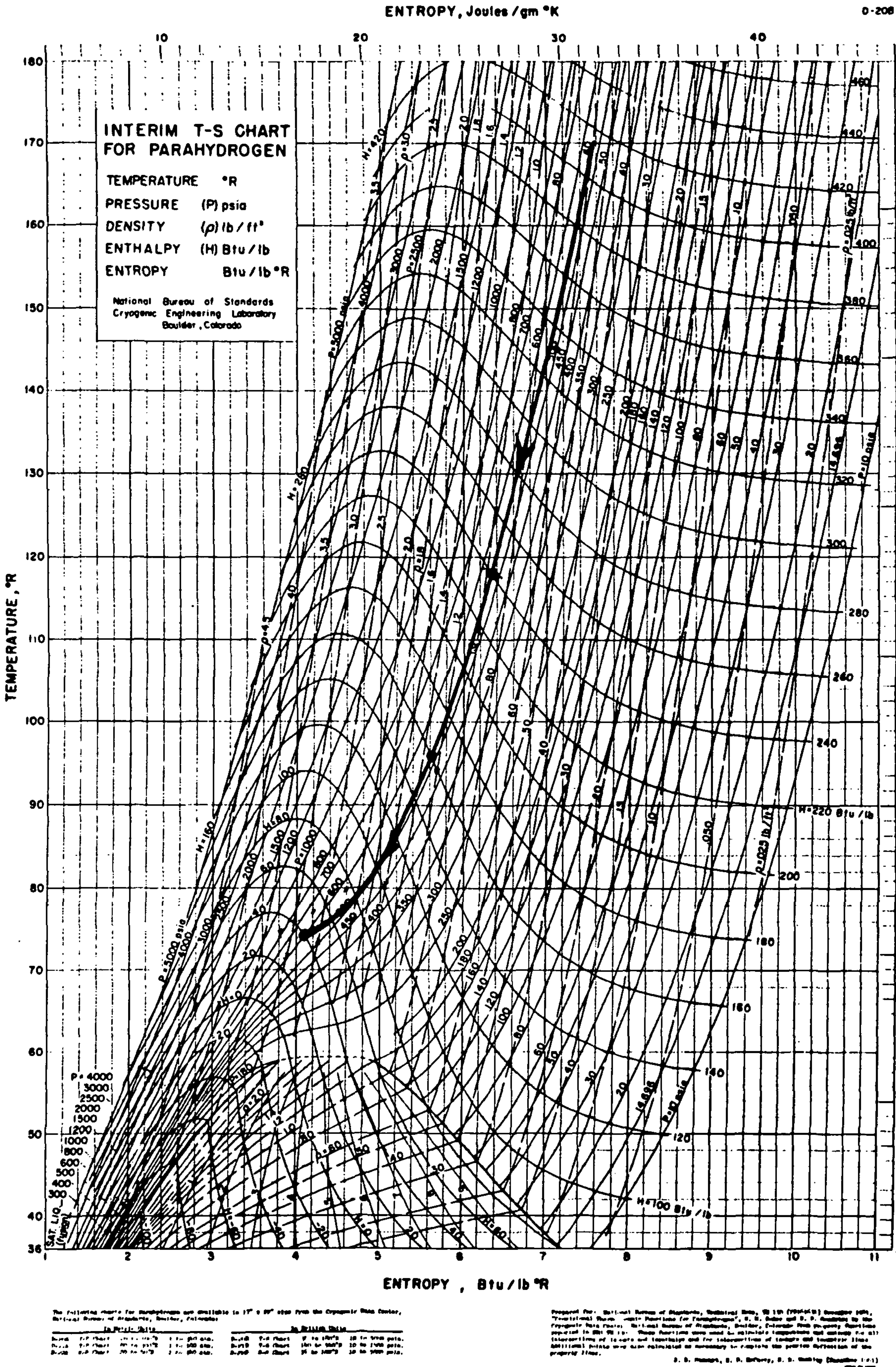


Fig. 10.5-4 Refill Process for Supercritical Hydrogen Tanks

are at a pressure of 600 psi, temperature of $74^{o}R$, and density of 2.73 lb/ft^3. If, during the refill process, it is necessary to raise the pressure to 600 psia from a minimum of 500 psi, it would take approximately 10 sec if the fluid withdrawal rate is on the order of 2.5 to 3 lb/sec.

With these fill conditions, the amount of oxygen to be refilled is 1,520 lb and the hydrogen is 710 lb. To evaluate the approximate influence of refill time, a trade study of pump system weight versus refill time was conducted. The refill quantities assumed are those given above. Results are shown in Fig. 10.5-5. The system weights are based on pumps and electric motors, with the power assumed to be provided by either fuel cell or an alternator on an APU. It can be seen that optimum transfer times for an APU-driven system are about 1000-to-1500 sec for the hydrogen and about 300 sec for the oxygen. For a fuel-cell-driven system, no definite optimum occurs; however, if powers less than 15kW are to be encountered, refill times greater than about 3,300 sec for the hydrogen and about 350 sec for the oxygen should be employed. For conditions at the optimum refill times, a list of weight changes for a refill system is shown in Table 10.5-10. The weights are based on a refill system for oxygen and hydrogen as shown in Figs. 10.5-6 and 10.5-7, respectively. The list of components is shown in Table 10.5-11. In order to refill the oxygen tanks, two tanks are required: one to be filled and permitted to go subcritical while one is for operation. It can be seen from Table 10.5-10 that a significant weight savings (2,036 lb) can be realized by utilization of the refill system as compared to a system where all the ACPS + FC + APU + EC/LSS cryogens are stored in supercritical tanks. However, this is not accomplished without the added complexity of valves, pumps, acquisition systems, and APU restarts.

10.5.5 Start Tanks As Part of Integrated Systems

A tradeoff study was conducted on an integrated system with a start tank incorporated in the hydrogen side of the system. The integrated system evaluated is shown schematically in Fig. 10.5-8, and all cryogens used in the various subsystems are contained in one hydrogen and one oxygen tank.

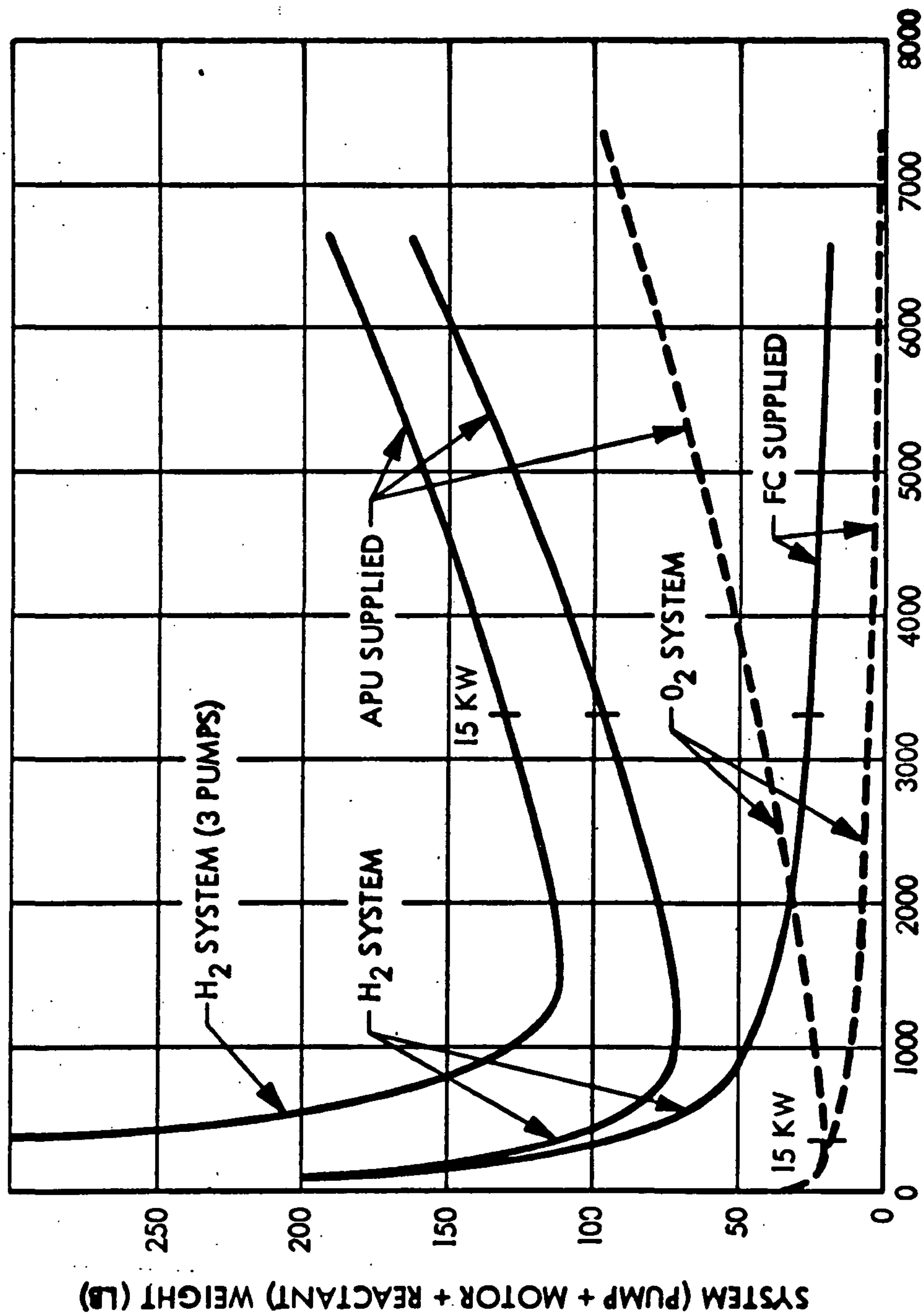


Fig. 10.5-5 Weight Trade for Propellant Transfer to Supercritical Tanks

Table 10.5-10

REFILL COMPARISON FOR ACPS + FC + APU + EC/LSS

	NO REFILL	REFILL	WT
O_2 Tank	1,020	280	-740
Insulation	8	3	-5
Vacuum Jacket	59	16	-43
H_2 Tank	3,600	2,240	-1,360
Insulation	61	39	-22
Vacuum Jacket	217	138	-79
O_2 Residual	515	113	-402
H_2 Residual	203	72	-131
Added Components	-	370	+370
Added Conditioning	-	53	+53
Added Storage, OMPS Tanks	-	123	+123
Acquisition	-	200	+200
TOTAL WEIGHT SAVINGS			2,036

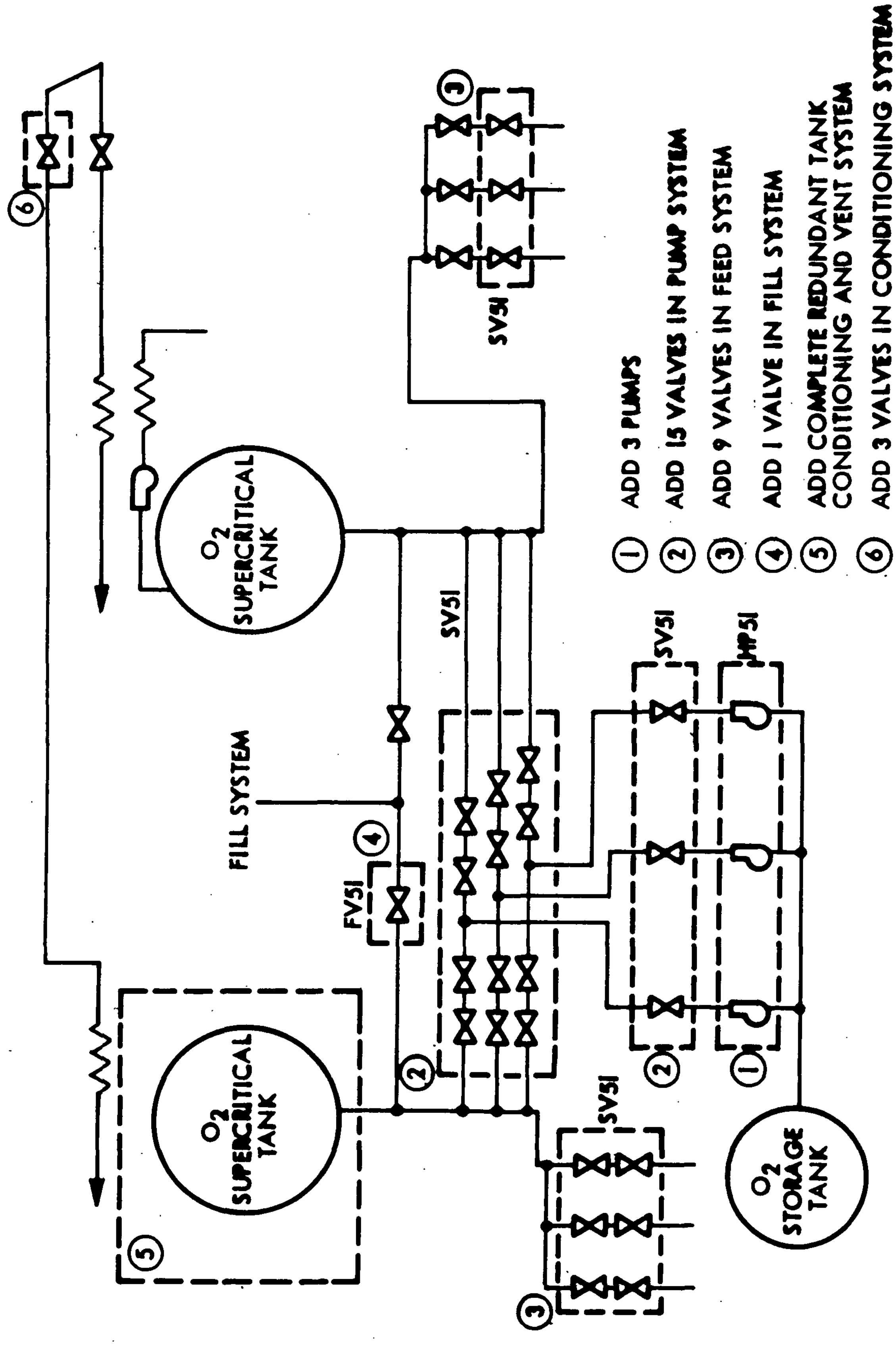


Fig. 10.5-6 O_2 Refill System

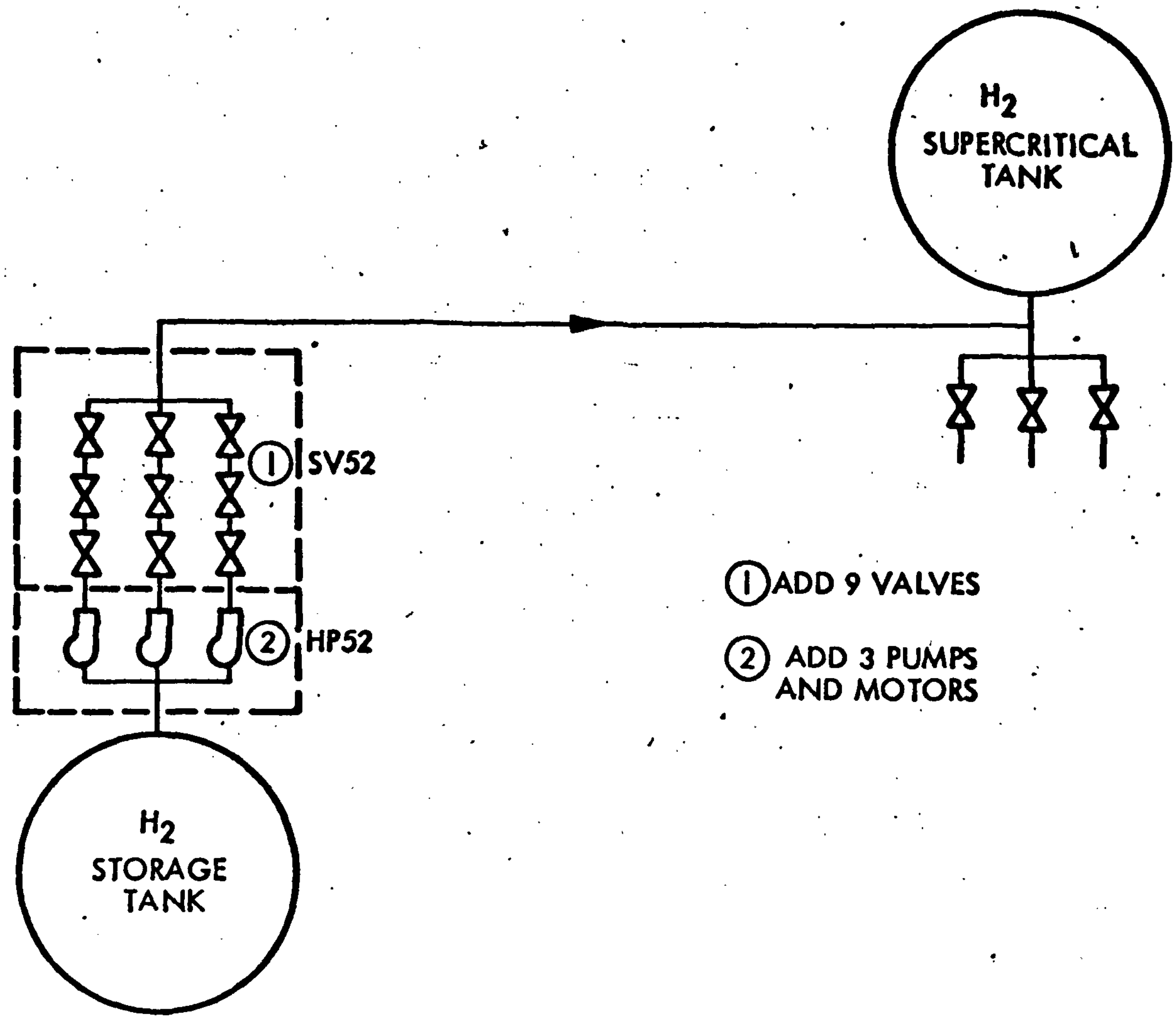


Fig. 10.5-7 H_2 Refill System

Table 10.5-11

COMPONENTS ADDED FOR REFILL SYSTEM

COMPONENT	NO.	WEIGHT (lb)	
VV51	1	4.2	O_2
PS53	4	0.5	O_2
BD51	1	0.2	O_2
RV51	1	3.8	O_2
FV51	1	10.2	O_2
SV51	24	147.1	O_2
HP51 (Including Motor) (1.7 + 8.5 = 10.2)	3	30.6	O_2
HX53 (7 lb)	3	21.0	O_2
CF51	3	6.0	O_2
SV52	9	65.7	H_2
HP52 (Including Motor)	3	81.0	H_2
		370.3	

The approach to the analysis was (1) to provide a list of assumptions and groundrules (see Table 10.5-12), (2) establish a typical mission duty cycle that would maximize start tank requirements (Tables 10.5-13 and 10.5-14), (3) size the start tank (Table 10.5-15), (4) determine the optimum system characteristics (Table 10.5-16), and (5) determine a detailed system weight (Table 10.5-17).

A five-burn, three-revolution rendezvous mission was used to evaluate the system. This mission was used,since it should result in one of the more difficult missions for a start tank type of system because:

- There are only five OMPS burns
- ACPS ΔV burns are performed (+X) between orbit transfer and retro-burns
- Some refill times are short
- Time between potential refill burns is maximized.

The above approach resulted in a requirement that the start tank should hold 2,046 lb of usable propellant between refills. Propellant usage as a function of mission time is shown in Tables 10.5-14 and 10.5-16, and the amount of propellant allocated to the various system functions is detailed in Table 10.5-12.

In determing the system characteristics (since pumps at the tank were assumed), a pump start transient midway between that of an RL-10 and the new transient used in LMSC work on this study was assumed, i.e., O_2 $\ddot{m}$ = 64.8 lb/sec^2 and H_2 $\ddot{m}$ = 12.8 lb/sec^2 at an 8K lb thrust level. Valve pressure drops were calculated using the data supplied by AiResearch under contract to LMSC. Line pressure drops were calculated taking into consideration typical line routings and components such as bellows or PVCs.

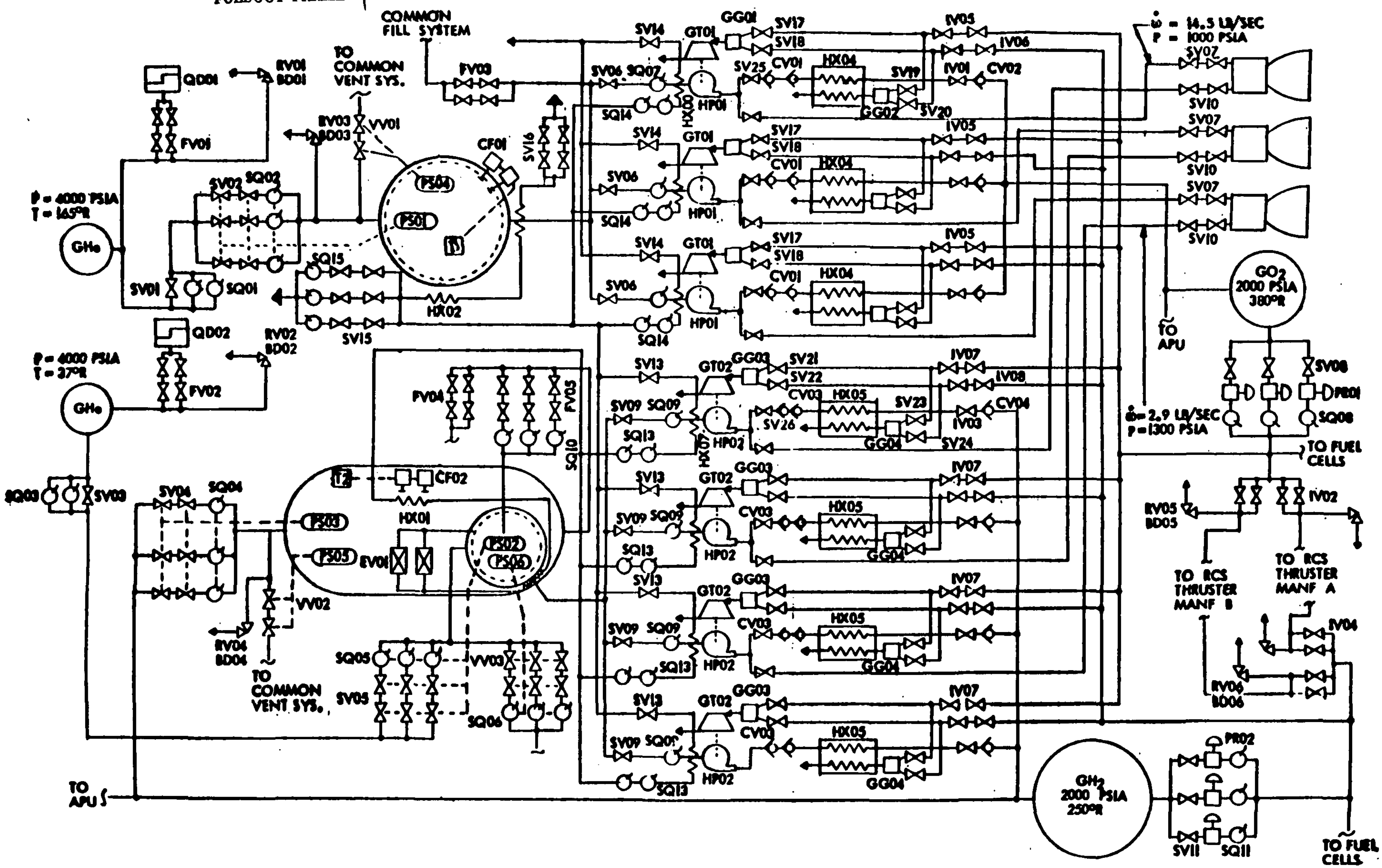


Fig. 10.5-8 Integrated OMPS/ACPS with Common Pumps

Table 10.5-12

GROUNDRULES AND ASSUMPTIONS

- All tanks were sized for 3% ullage and 1% liquid residuals except for the LH_2 start tank, which was sized for 1½% liquid residuals.
- Tank sizing was based on a completely integrated system for all cryogenic fluids and an orbit ΔV capability of 2000 ft/sec with 185 ft/sec allotted to the ACPS.
- On-orbit ΔV maneuvers in the +X direction were accomplished by firing two 8000-lb-thrust pressure-fed thrusters simultaneously, but three 8000-lb-thrust thrusters were installed. OMPS thruster specific impuse of 459.8 seconds was assumed.
- The common propellant pumps sized for supplying the 8000-lb-thrust thrusters and for ACPS use were operated as required.
- Only single-tank systems were evaluated with an assumed aft location. The oxidizer tank was assumed spherical, and the hydrogen tank had a 12-ft diameter.
- HPI with a purge bag was assumed on the hydrogen main tank, and the H_2 start tank had one inch of polyurethane foam. The oxidizer tank was vacuum jacketed to reduce boiloff during the reentry and landing phases of the flight. Optimum insulation thicknesses of 2 in. and 0.8 in. of Superfloc for the H_2 and O_2 tanks, respectively, were used in all calculations.
- All lines were vacuum jacketed with HPI within the jackets.
- No hydrogen was vented below 160,000-ft altitude.

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Table 10.5-12 (Cont.)

- LH_2 insulation on the main tank was ground purged with helium supplied from a ground source. The helium vented from the purge cavity as the vehicle climbed out, and venting was assumed complete as the vehicle reached an altitude pressure of 10^{-5} torr.

- Main tank hydrogen vapor pressure was maintained by a TCU at the 21.5-psia reached in the tank at the time venting could begin.

- The H_2 start tank and the O_2 tank were pressurized by helium supplied at their respective cryogenic temperatures. Separate helium storage at an initial helium storage pressure of 4000 psia was assumed, and the helium storage tanks were mounted outside the propellant tanks under the HPI.

- Only hydrogen was vented for tank, line, and pump cooling. Venting was through a thermal conditioning unit, and the vented hydrogen gas was used to cool the oxidizer tank, lines, and pumps.

- The H_2 main tank was pressurized by gas from the H_2 accumulator. The accumulator also supplied gas to the fuel cell, APU, ACPS, EC/LSS, and the gas generators for the conditioning heat exchangers and the common pumps.

- Component redundancy was added to meet fail-operational/fail-safe criteria.

- ACPS thruster weight, feed lines to the thrusters, and required valving were not included in the weight summary. Lines and valves to the fuel cells, APUs, and EC/LSS also were not included.

- Propellant acquisition devices were installed in the O_2 tank and the H_2 start tank. The devices have zero "g" all-axis withdrawal capability.

- Minimum NPSP for the oxidizer and hydrogen pumps was 4 and 2 psia, respectively.

Table 10.5-13

INTEGRATED SYSTEMS - LH_2 ON-ORBIT STORAGE TANK USAGE (START TANK APPROACH), VACUUM JACKET

Event	Mission Elapsed Time (hr)	Δt From Last Event (hr)	Event Δt (sec)	GH_2 ACCUMULATOR OUTFLOW: FC	APU	ACPS	OMPS .35 lb/sec	Main Tank Pressr.	O_2 Accum Recharge 3.1 lb/chg	Accum. Usable Quant.	START TANK OUTFLOW: Accum. Resup.	Cooling 5.56 lb/hr	OMPS 40.6 /start	ACPS	Cum Since Refill	Start Tank Quant.	Helium Vented From Start (lb.)	Main Tank Outflow (lbs.)	Main Tank Quantity (lb.)
Launch	0	0	-	NIL	-	-	-	-	-	22	-					2046			6484
Injection	0.12	0.12	407	-	78	-	-	-	3.1	6.9(3)	85.2	-	-	-	85.2	1961			6484
Pre Phasing Burn		0.71	-	3.0	-	12.1	-	-	3.1	10.7(1)	28.4	3.9	-	-	117.5	1929			6484
Phasing Burn	0.83	-	7	-	-	-	2.5	1.2	-	7.0	-	-	40.6	-	158.1	1888			
Phasing Burn (+7)	-	-	207.6	-	-	1.6	72.7	6.1	3.1	11.5(4)	-	-	-	-	158.1	1888		1311	5173
Height Adj Burn	1.58	0.75	7	1.0	-	0.4	2.5	1.9	-	5.7	-	4.2	40.6	-	202.9	1843			
Height Adj Burn (+7)	-	-	159.6	-	-	1.6	55.9	4.4	3.1	6.7(3)	-	-	-	-	Refill	2046	1.86	1208	3965
Coelliptic Burn	2.37	0.79	7	NIL	-	0.3	2.5	2.5	-	1.4	-	4.4	40.6	-	45.0	2001		-	
Coelliptic Burn (+7)			8.3			0.2	2.9	0.2	3.1	17.0(1)	-	-	-	-	45.0	2001		74	3891
Dispersion Burn (ACPS)	3.11	0.74	10	1.0	-	43.1	-	2.5	-	-	27.7	4.1	-		76.8	1960		--	
Dispersion Burn (+10)			34.7			163	-	0.5	-	22(1)	3.5	-	-		80.3	1966		163	3728
TPI Burn	3.85	0.74	7	1.0	-	15.9	2.5	2.6	3.1	18.9(1)	28.4	4.1	40.6	-	153.4	1893		-	
TPI BURN (+7)			5.9			-	-	0.2	-	18.7	-	-	-	-	-	-		34	3694
MCC-1 (ACPS)	4.05	0.2	10	0.3	-	41.6	-	2.5	-	Transient	26.4	1.1	-	-	180.9	1865			
MCC-1 (+10)			54.1	-	-			0.6	-	22	-				Refill	2046	1.66	384	3310
Accum Refill After Burn						-			-	22	54.1	-	-	-	54.1	1992			
MCC-2 (ACPS)	4.21	0.16	10	0.3	-	56.5		2.9		Transient	22.9	0.9	-	-	77.9	1968		-	
MCC-2 (+10)			23.8							"	-				Refill	2046	0.71	206	3104
						0.6				21.4	23.2				23.2	2023			
On Orbit Use	166.57	162.36		165.4	5	429.4	-	-	255.7	22		902.7	-		1781.4	265			
Retro Burn	166.57	162.36	7	-	-	0.4	2.5	3.0	-	16.1	-	-	40.6		1822.0	224		-	3104
Retro Burn (+ 7 Sec)			242.2			1.8	84.8	7.0	3.1						Refill	1722		3040	64

Table 10.5-14

INTEGRATED SYSTEMS LO_2 ON-ORBIT STORAGE TANK USAGE

Event	Mission Elapsed Time (hr)	Δt From Last Event (hr)	Event Δt (sec)	GO_2 Accumulator Outflow						
				FC	APU	LSS .32 lb/hr	ACPS	OMPS .35 lb/sec	H_2 Acc. Recharge (6.4 lb/chg)	Accum. Usable Qty (lb)
Launch	0	0		Nil	Nil		-	-	-	78
Injection	0.12	0.12	407	Nil	70		-	-	19.2	66.8(1)
Phasing - Pre-Burn		.71	-	25	-	0.2	48.4	-	6.4	64.8(1)
Phasing - Burn	0.83		7	-	-	-	3.2	2.5	-	59.1(1)
Phasing - Burn + 7 sec			207.6	-	-	-	3.2	72.7	25.6	35.6
Height Adjust - Burn	1.58	0.75	7	7	-	0.2	1.6	2.5	-	24.3(1)
Height Adjust - Burn + 7			159.6				6.4	55.9	19.2	20.8
Coelliptic - Burn	2.37	0.79	7	8	-	0.3	1.2	2.5	-	8.8(1)
Coelliptic - Burn + 7		0.79	8.3		-		0.8	2.9	6.4	76.7
Dispersion - Burn (ACPS)	3.11	0.74	10	7	-	0.2	200	-	-	
Dispersion - Burn + 10			34.7					-		78
TPI - Burn	3.85	0.74	7	8	-	0.2	63.6	2.5	6.4	75.3(1)
TPI - Burn + 7			5.9		-	-	-	2.1	-	73.2
MCC - 1 Burn (ACPS)	4.05	0.20	10	2	-	Nil	817.2	-		
MCC - 1 Burn + 10 sec)			54.1				63.2			69.9
MCC-2 BURN (ACPS)	4.21	0.16	10	1	-	0.1				
MCC-2 + 10			23.8							
Post Burn Access Refill										78
On-Orbit Use	166.57	162.36		1372	4	51.9	1717.6	-	255.7	

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Table 10.5-15

LH_2 START TANK PROPELLANT QUANTITIES

	LH_2
ACPS Impulse	642
Fuel Cell	165
Thruster Childown	5
Cooling - Pumps	488
- Tanks	304
- Lines	106
Conditioning	336
Total LH_2	2046 lb

Table 10.5-16

SYSTEM CHARACTERISTICS

Main LH_2 Tank Operating Pressure	30.4 ± 1 psia
LH_2 Start Tank Operating Pressure	26 ± 1 psia
LO_2 Tank Operating Pressure	24.4 ± 1 psia
LH_2 Tank Volume	2430 ft^3
LO_2 Tank Volume	578 ft^3
LH_2 Start Tank Volume	484 ft^3
GH_2 Accumulator Volume	47.8 ft^3
GO_2 Accumulator Volume	11.1 ft^3
OMPS Nominal Thrust	16000 lb
ACPS Nominal Thrust	1750 lb/thruster
Nominal OMPS Flow Rate (per thruster)	O_2 - 14.5 lb/sec H_2 - 2.9 lb/sec
ACPS Nominal Max Flow Rate	O_2 - 9.78 lb/sec H_2 - 2.43 lb/sec

Table 10.5-17

INTEGRATED SYSTEMS WEIGHT (H_2 START TANK)

SUBSYSTEM	
Ground/Flight Vent	
• Components	81
• Lines	63
	144
Fill/Drain & Feed	
• Valves	665
• Lines (incl. bellows, etc.)	705
• Propellant Tanks	2,761
• Tank Insulation	241
	4,372
Pressurization	
• Valves and Switches	83
• Pressurant Storage Spheres	135
• Lines	8
	226
Propellant Conditioning	
• Valves, Controls, etc.	349
• Heat Exchangers	90
• Acquisition Devices	131
• Turbopumps	209
	779
Subsystem Totals	5,521
OMPS Thrusters (3)	300
Total Dry Weight (lb)	5,821

Table 10.5-17 (Cont.)

Fluids		O_2	H_2
• Impulse Propellants			
- OMPS		22,340	4,468
- ACPS		5,230	1,310
• Cryogens			
Fuel Cell		1,450	175
APU		294	327
EC/LSS		50	0
OIPS Prepressurant		2	5
OMPS Pressurant		0	32
OMPS GG		277	277
Conditioning		756	756
Cooling - Pumps		-	504
- Tanks		-	314
- Lines		-	110
	Subtotals	30,392	8,278
• Residuals - Liquid		390	95
- Gas		239	245
• Dumped Propellants		6	1
		31,027	8,619

Summary:

Total O_2	31,027
H_2	8,619
Pressurant	77
Total Fluids (lb)	39,723
System Dry Weight	5,821
Total Weight (lb)	45,544

Main tank, line, and pump cooling requirements were determined by using previous studies for the OMPS and extrapolating for the larger size tanks; in the case of pump cooling requirements, the APS technology contract data were used. The accumulators were sized to hold 22 lb and 78 lb of usable propellant for the H_2 and O_2, respectively. The amounts were determined by reviewing probable usage requirements from the mission duty cycles and then fixing a size that would reduce turbopump cycle requirements to an acceptable number. The accumulator usable quantities were based on an isentropic blowdown from the initial conditions shown in the schematic, i.e., 2000 to 1000 psia. The approach on accumulator operation was to assume that a pressure switch would actuate at 1100 psia and start a turbopump and its respective heat exchanger.

In the case of the O_2 system, since the pump was sized for OMPS operation, it was oversized for the ACPS requirement. A net increase in accumulator pressure would occur even though ACPS flowrates were at their most probable maximum.

The H_2 side of the system was a different case. A single H_2 pump, sized for OMPS use, was undersize for the most probable ACPS flowrates (2.9 vs 3.64 lb/sec or a maximum of 4.29 lb/sec), and during ACPS operations, two H_2 turbopumps would operate for ACPS burns of approximately 15 seconds and longer. Since an H_2 turbopump also has to operate during OMPS burns of approximately 63 seconds and longer, a fourth H_2 turbopump was added to the system so the OMPS would be subjected to minimum impact during retroburn after a double malfunction of H_2 turbopumps.

An extra oxygen turbopump is not required, because the oxygen accumulator can hold sufficient propellant so that resupply is not required during the retroburn. An alternate operating mode would have to be employed, however, and would consist of recharging the oxygen accumulator to maximum capacity just prior to retroburn and then letting it blowdown (900 psia) during the burn.

While this would be slightly under the normal pressure-switch setting, it leaves an adequate reserve before absolute minimum pressure is reached (500 psia) and is the recommended method of operation.

The refill of the start tank had to be accomplished for a total of four times to minimize the size of the start tank. The largest refill occurred during the retroburn and established the size of the transfer line between the main tank and the start tank. Three other refills were required because of the short times available for refill. The method of refill was as follows:

- The OMPS or ACPS +X burn operation would begin by propellant supply from the start tanks.

- When propellants were settled (7 and 10 sec, respectively for the OMPS and ACPS), the transfer-line shutoff valves would be opened. Concurrently with propellant settling, the main tank would be pressurized by gaseous hydrogen supplied from the hydrogen accumulator.

- The start tank vent valves would be opened and adequate pressure (~ 26 psia) maintained in the start tank with the main tank supplying both propellants to the operating thrusters and refilling the start tank.

The above approach resulted in a transfer-line optimum diameter of 5.5 in. This relatively large size was due to the high flowrate required to refill the tank and supply the two OMPS engines simultaneously. Assuming that the start tank would be basically empty and that the refill should be completed in a time 10 percent less than the available time, the total flowrate calculated was 15.3 lb/sec.

While detailed conclusions cannot be made between a start tank type approach versus other approaches, due to the lack of detailed evaluations on all the

approaches, the present study does allow a number of general conclusions to be made. These are:

- The start tank approach reduces helium requirements by a factor of approximately 2.5 for a completely integrated system where the pumps (ACPS or common) must be ready to go at all times.

- The start tank approach eliminates the need for vacuum-jacketed tanks in integrated systems, as cryogen boiloff during atmospheric flight can be reduced by use of foam insulation on the start tank exterior.

- The start tank approach is lighter than a vacuum-jacketed system for a completely integrated system but is heavier than a nonvacuum-jacketed approach. A nonvacuum-jacketed approach with a hardshell purge bag with foam insulation on the purge bag exterior should result in the lightest system.

- The start tank approach is duty-cycle limited unless the start tank is sized large. A larger size start tank can result in a heavy system, as the start tank is subjected to externally imposed crushing pressures. These crushing pressures could be the most critical aspect of a start tank approach when safety is considered.

- The start tank approach complicates tank fabrication and adds complexity to system operation.

- Pump at-the-tank should be lighter than pump at-the-engine due to lower ullage pressure requirements resulting from low-pressure losses during start transients and flow due to the shorter feed lines.

10.5.6 Propellant Utilization Examinations for Integrated OMPS/ACPS System

A study was performed to determine the propellant usage uncertainties of the integrated OMPS/ACPS and to determine the amount of either O_2 or H_2 loading bias to assure adequate propellant is available to perform all the required functions. Two approaches in determining the amount of loading bias were considered. Since the RL-10 engine has mixture ratio control, the mixture ratio can be varied to account for the uncertainties in usage. This mixture ratio control is utilized during the last engine operation (retro maneuver) for the first approach. The second approach did not take advantage of the mixture ratio control and both the O_2 and H_2 loading must be biased to account for the performance deviations. The performance uncertainties used in this study are summarized in Table 10.5-18. The mission considered was the seventeenth revolution rendezvous case. Using these performance uncertainties, the resulting O_2 and H_2 uncertainties are shown in Table 10.5-19. The mixture ratio of the RL-10 engine can be controlled between 4.4 and 5.6, the resulting delta O_2 and H_2 weights (based on 5.0 nominal) are shown in Fig. 10.5-9 as a function of mixture ratio selected for the retro burn. The delta weights shown are the negative of the delta weights used by the engine. For example, if a mixture ratio of 4.4 were selected, the engine would use 211 lb less O_2 than if a ratio of 5.0 were used or a delta weight of -211 lb O_2. However, this is plotted as a +211 lb delta weight in order to be consistent with the sign of the usage uncertainty. That is, if during previous ACPS and OMPS usage, an excess of 211 lb of O_2 had been used, then a ratio of 4.4 could be selected for the retro burn which is 211 lb less O_2 than nominal, with the result that the O_2 usage is now balanced out.

Taking the RSS values of the O_2 and H_2 usage uncertainties for all functions except the retro burn results in an O_2 usage uncertainty of +77.98 lb, -85.27 lb and the corresponding H_2 uncertainty is +103.57 lb and -97.66 lb. These are plotted in Fig. 10.5-9. These uncertainties result in two ways of biasing the propellant loading. If O_2 depletion is desired, then a mixture ratio of 4.77 is selected with the result that an additional 170 lb

Table 10.5-18

OMPS/ACPS PERFORMANCE UNCERTAINTIES

OMPS Engine Mixture Ratio	5.0 ± 0.1	
ACPS Engine Mixture Ratio (Pulsing)	4.0 ± 0.5	
ACPS Engine Steady State O_2 Feed Pressure	± 2.5%	MR = 4.00 $^{+.1156}_{-.0908}$
ACPS Engine Steady State H_2 Feed Pressure	± 2.5%	
ACPS Engine Steady State O_2 Feed Temperature	± 2.5%	
ACPS Engine Steady State H_2 Feed Temperature	± 2.5%	
ACPS Conditioning Mixture Ratio	1.00 $^{+.0289}_{-.0277}$	
O_2 Vapor Residual Equilibrium Temperature	164 ±1°R	
H_2 Vapor Residual Equilibrium Temperature	38 ±1°R	
O_2 Pump Chilldown O_2 Usage	± 1 lb Per Start	
H_2 Pump Chilldown H_2 Usage	± 1.2 lb Per Start	
ACPS Pump Cooling H_2 Usage	± 10%	
Tankage and Line Cooling H_2 Usage	± 10%	
O_2 Loading Deviation	±0.0916%	
H_2 Loading Deviation	±0.278%	

Table 10.5-19

OMPS/ACPS USAGE TOLERANCE

Function	O_2			H_2		
	+	NOM	-	+	NOM	-
OMPS Pre-Retro	50	15411	52	52	3082	50
ACPS TCA's	51	5159	60	60	1289	51
ACPS Conditioning	7	495	6	6	495	7
OMPS Pump Chill-down (11 Burns)	11	110	11	13.2	55	13.2
ACPS Pump Cooling	-	-	-	50	504	50
Tank & Line Cooling	-	-	-	16	158	16
Vapor Residuals	9.5	170.2	8.4	32.5	216.7	28.2
Loading Tolerances	27	-	27	20	-	20
Overall RSS	77.98		85.27	103.57		97.66
OMPS Retro (W/O MR Control)	26	7177	26	26	1544	26
Overall RSS (W/O MR Control	82.2		89.1	106.8		101.1
RL-10 Control During Retro Burn	+211		-194.1	+127.6		-166.4

Bias Required with MR Control During Retro:

For H_2 Bias, Select MR for Retro = 4.77 and Add 170 lb of H_2

Or

For O_2 Bias, Select MR for Retro = 5.49 and Add 238 lb of O_2

Bias Required W/O MR Control: Add 82.2 lb of O_2

Add 106.8 lb of H_2

189.0

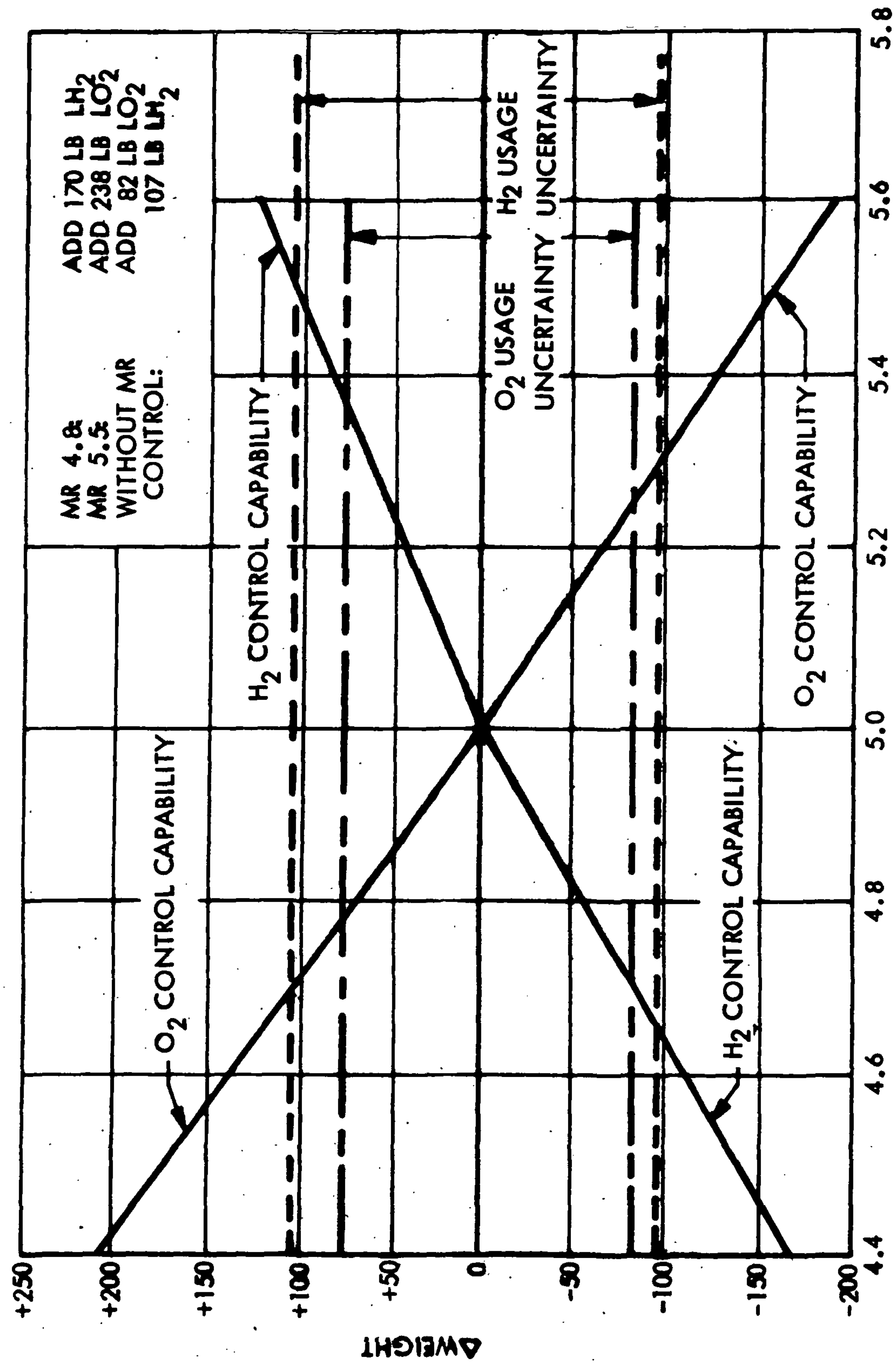

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Fig. 10.5-9 Compatibility Between Propellant Usage Uncertainty and Propellant Usage Control

of H_2 must be loaded or, if H_2 depletion is desired, then a ratio of 5.49 is selected with the result that an additional 238 lb of O_2 must be loaded. Of these two options, it is better to bias the H_2 loading and, then, add 170 lb to the H_2 loading.

If no mixture ratio control is used, then the overall O_2 usage uncertainty is +82.2 lb and -89.1 lb and for the H_2 +106.8 and -166.4 lb. The required propellant loading bias would then be +82.2 lb of O_2 and +106.8 lb of H_2 for a total of 189.0 lb additional propellant loading or 19 lb more than if mixture ratio control is used during the retro burn.

For both of these cases, open loop propellant utilization can be employed and no zero-g gaging system would be required.

SECTION 11

COMPONENT EVALUATIONS

Component evaluations were planned to provide information in depth regarding the required cryogenic supply components. The information includes the following, as applicable to the components under consideration:

- Component descriptions for each identified application, relating where possible to existing hardware
- Analyses supporting a particular component selection or approach
- Parametric data regarding a number of component parameters, as applicable to the components under consideration
- Reusability evaluations
- Malfunction information
- Component effects upon reliability

As previously presented, Lockheed and the AiResearch Manufacturing Company performed the component evaluations and selections. In addition, information was obtained from other cooperating suppliers.

11.1 COMPONENT DATA COMPILATION

This subsection discusses the component selection and parametric data collection for the components. Reusability, malfunction, reliability, and technology evaluation data are discussed in other subsections.

11.1.1 Component Selection Data from AiResearch

11.1.1.1 Component Selection. In the collection of component data, a major step was the contribution of component data from AiResearch. The discussions regarding the preparation of the schematics are presented with each subsystem. These schematics, presented in Appendix E are summarized as follows:

- Orbit Maneuvering Propellant Supply
  - (1) Helium Pressurized Tanks
  - (2) GO_2/GH_2 Pressurized Tanks (with Boost Pump)
- Orbit Injection Propellant Supply
  - (1) Helium Prepressurized with On-Off Pressurization
  - (2) GO_2/GH_2 Prepressurized with Regulated Pressurization
- Attitude Control Propellant Supply
  - (1) Subcritical Storage
  - (2) Supercritical Storage
- Auxiliary Power Unit Supply
  - (1) Subcritical Storage
  - (2) Supercritical Storage
- Fuel Cell Supply
  - (1) Subcritical
  - (2) Supercritical
- Life Support Supply
  - (1) Subcritical Storage
  - (2) Supercritical Storage

- <u>Purge, Inerting, and Pneumatic System</u>
    - (1) Subcritical Nitrogen and Helium Stored at Cryogenic Temperature
    - (2) Supercritical Nitrogen and Helium Stored at Ambient Temperature

In addition to the schematics, Lockheed provided to AiResearch information regarding the component requirements, such as flowrates, temperatures, number of cycles per mission, and lifetime.

AiResearch examined each of the subsystems through the use of a computer program and properly sized the valves with regard to pressure drop and other design characteristics. Then, AiResearch analyzed and selected components for each application in the subsystems for the following:

a. Valves and regulators
b. Disconnects
c. Heat exchangers
d. Pumps
e. Turbines
f. Control units
g. Pressure switches

For each of the components, data sheets were prepared containing information such as:

a. Sketch of geometry
b. Type, application, function
c. Type actuation
d. Actuating power requirements (as applicable)
e. Helium used per actuation (as applicable)

f. Response time

g. Flowrate, temperature, pressure

h. Pressure drop

i. "C" factor and CA

j. Geometric area

k. Closure element diameter

l. Closure element position (NO or NC)

m. Leakage

n. Weight

o. Similar drawing (as applicable)

p. Materials recommended for:

   (1) Body
   (2) Actuator
   (3) Seat
   (4) Rotary seals
   (5) Static seals
   (6) Butterfly seals

The data sheets for the components are presented in the Space Shuttle Cryogenic Supply System Optimization Study Task Reports. These represent a very extensive collection of data.

11.1.1.2 <u>Parametric Data</u>. Certain of the component types examined by AiResearch were selected for the generation of parametric data. The intent of generating these parametric data was to provide information for performing the subsystem tradeoffs and necessary information for the Integrated Math Model. Components, for which parametric data were generated by AiResearch, were as follows:

11.1.1.2.1 Valve Parametric Data.

- Weight versus valve diameter parametric data were generated as presented in Table 11.1-1.

- Pressure drop versus weight flow parametric data were generated as presented in Table 11.1-2.

It was considered desirable only to include the valve parametric weight data in this report. These are presented in Figs. 11.1-1 through 11.1-7.

11.1.1.2.2 Heat Exchanger Parametric Data. The wide range of variation in temperatures, pressures, and flowrates of the fluids makes it impossible to present actual heat exchanger weights and volumes in a report of reasonable size. The approach taken, therefore, was to have the user determine those heat exchanger characteristics which can be easily calculated and use graphical data only when further calculations become impractical.

Instructions fall into two categories: those concerned with establishing a heat exchanger design point and those concerned with determining the weight and volume of a heat exchanger, given the design point. The design procedure is sometimes iterative, depending on whether or not a realistic heat exchanger exists for a given design point. This problem can occur only when pressure drops are specified by system demonstrations. The design procedures are shown in Fig. 11.1-8.

The following parameters must be defined before attempting to determine heat exchanger weight or volume:

ω_c = Flowrate of the cryogenic fluid

$T_{c,\,in}$ = Temperature of the cryogenic fluid at inlet

Table 11.1-1

WEIGHT VERSUS VALVE DIAMETER PARAMETRIC DATA

Weight Class	Valve Types
Light	Poppet type: check valves and quick disconnects
Medium	Butterfly type: modulation, shutoff, vent, fill, and isolation valves
Medium	Poppet type: modulation, shutoff, vent, fill, and isolation valves
Heavy	Butterfly type: pressure regulators, flow controls, pressure relief and mix valves
Heavy	Poppet type: pressure regulators, flow controls, pressure relief and mix valves
Extra Heavy	Butterfly type: solenoid and ball valves
Extra Heavy	Poppet type: solenoid and ball valves

Table 11.1-2

PRESSURE DROP VERSUS WEIGHT FLOW PARAMETRIC DATA

Size (inches)	Type	Flow Coefficient	Fluid (Liquid)
0.25 to 2.5	Butterfly	0.75	Oxygen
1.0 to 14	Butterfly	0.75	Oxygen
0.25 to 2.5	Poppet	0.65	Oxygen
1.0 to 14	Poppet	0.65	Oxygen
0.25 to 2.5	Ball (Visor)	0.85	Oxygen
1.0 to 14	Ball (Visor)	0.85	Oxygen
0.25 to 2.5	Disconnect	0.95	Oxygen
1.0 to 14	Disconnect	0.95	Oxygen
0.25 to 2.5	Butterfly	0.75	Hydrogen
1.0 to 14	Butterfly	0.75	Hydrogen
0.25 to 2.5	Poppet	0.65	Hydrogen
1.0 to 14	Poppet	0.65	Hydrogen
0.25 to 2.5	Ball (Visor)	0.85	Hydrogen
1.0 to 14	Ball (Visor)	0.85	Hydrogen
0.25 to 2.5	Disconnect	0.95	Hydrogen
1.0 to 14	Disconnect	0.95	Hydrogen

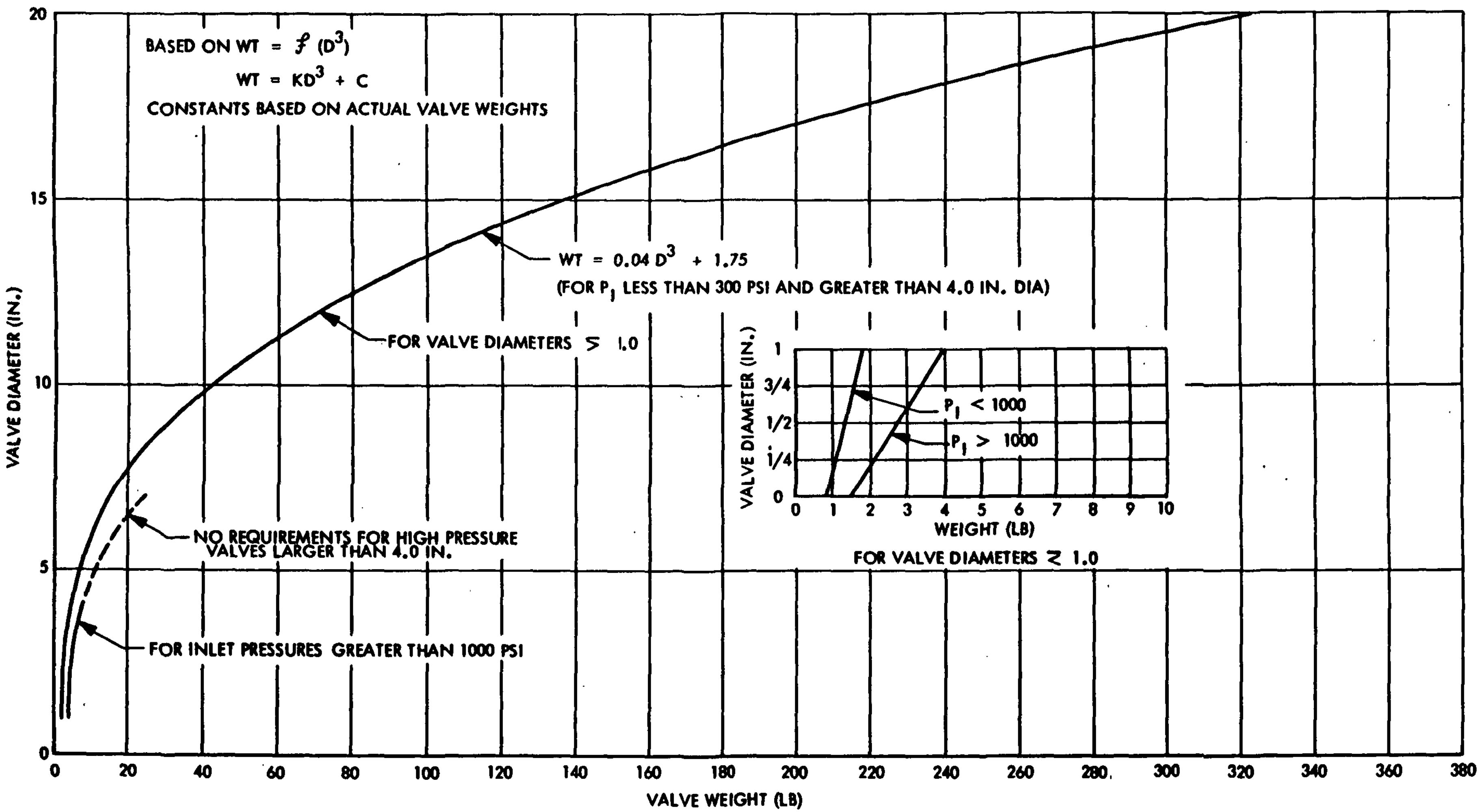

Fig. 11.1-1 Weight vs Valve Diameter (Estimate), Light Check Valves, Quick Disconnects, Poppet Type

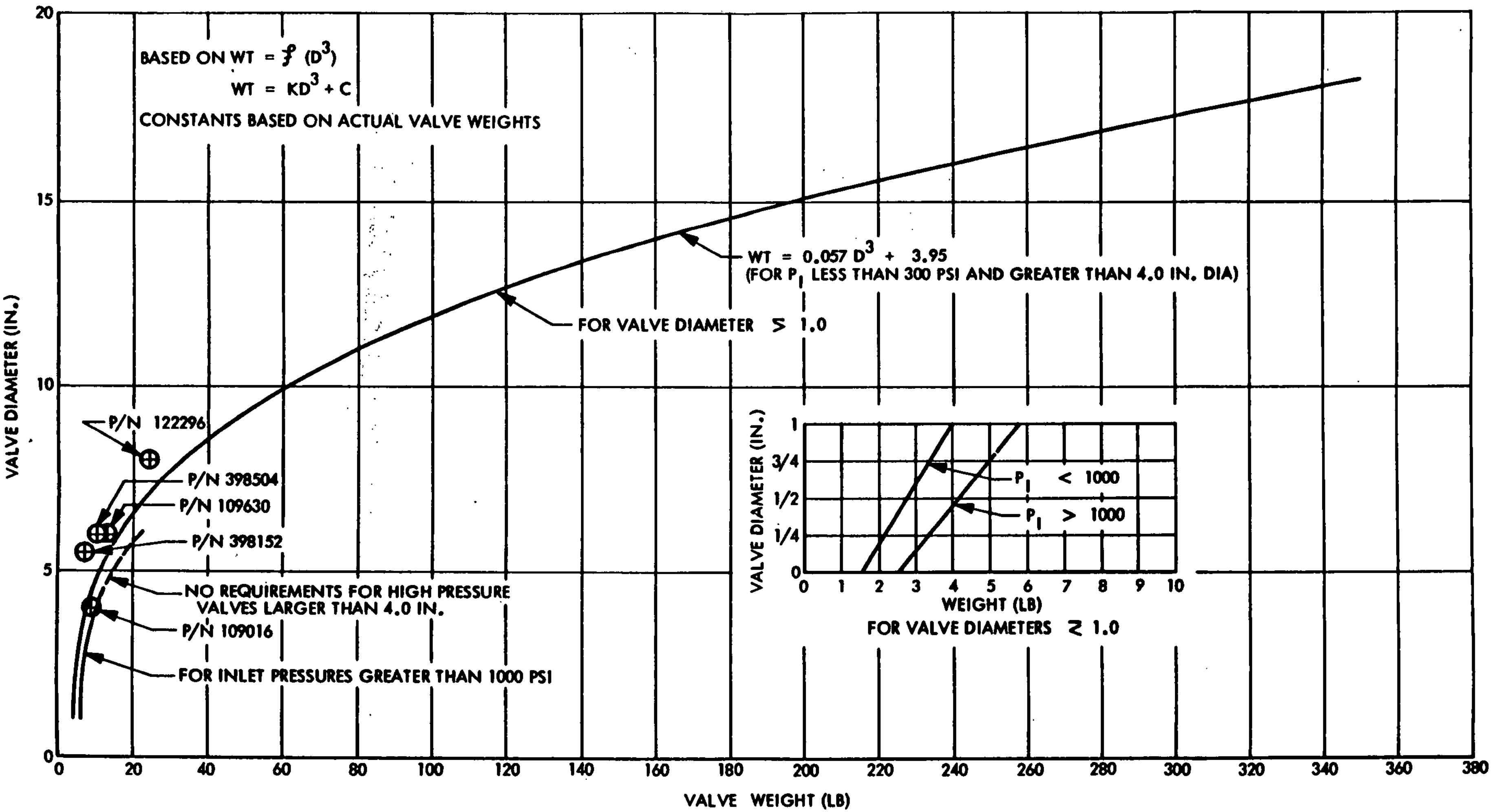

Fig. 11.1-2 Weight vs Valve Diameter (Estimated), Medium Modulation, Shutoff, Vent, Fill and Isolation Valves, Butterfly Type

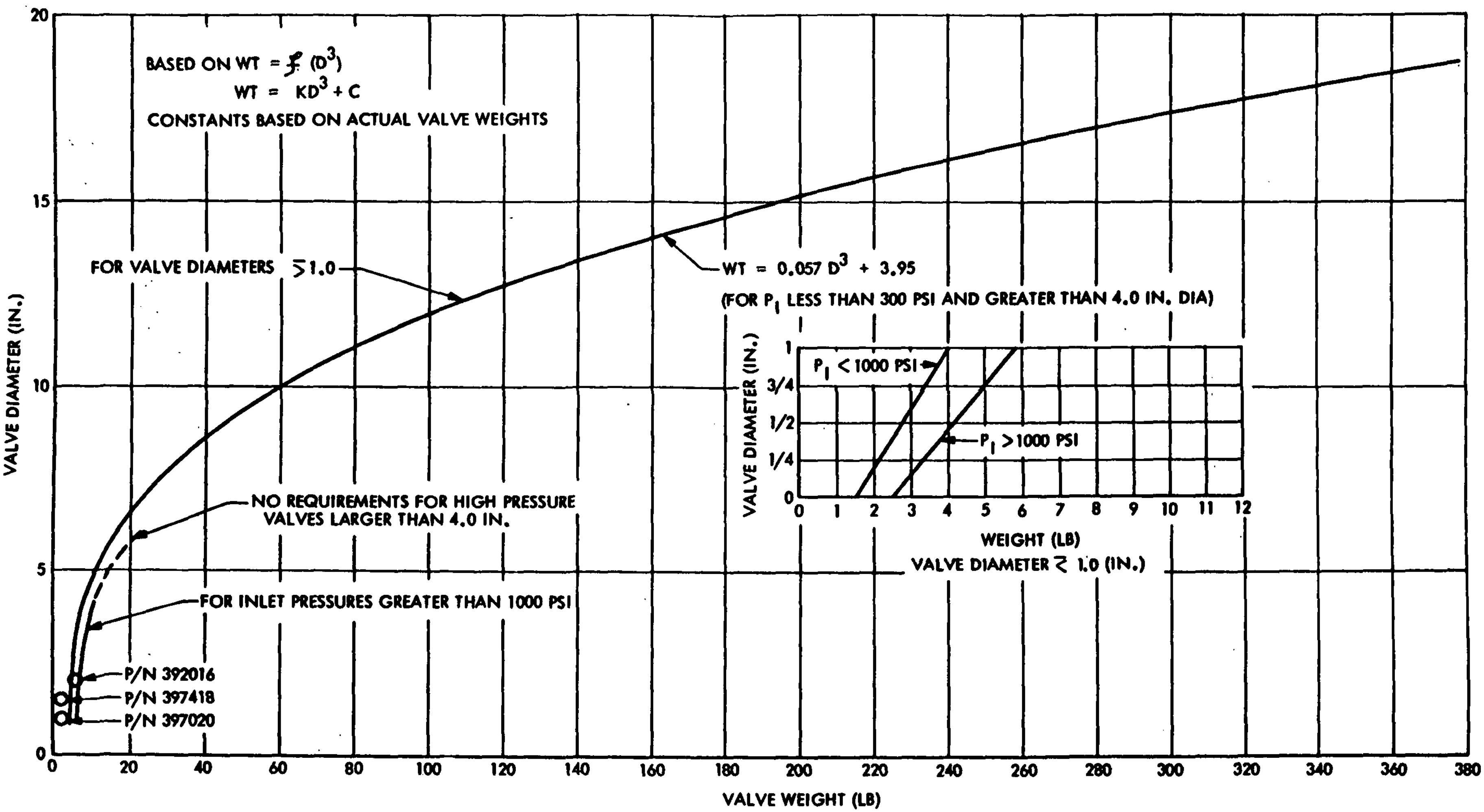

Fig. 11.1-3 Weight vs Valve Diameter (Estimated), Medium Modulation, Shutoff, Vent, Fill and Isolation Valve, Poppet Type

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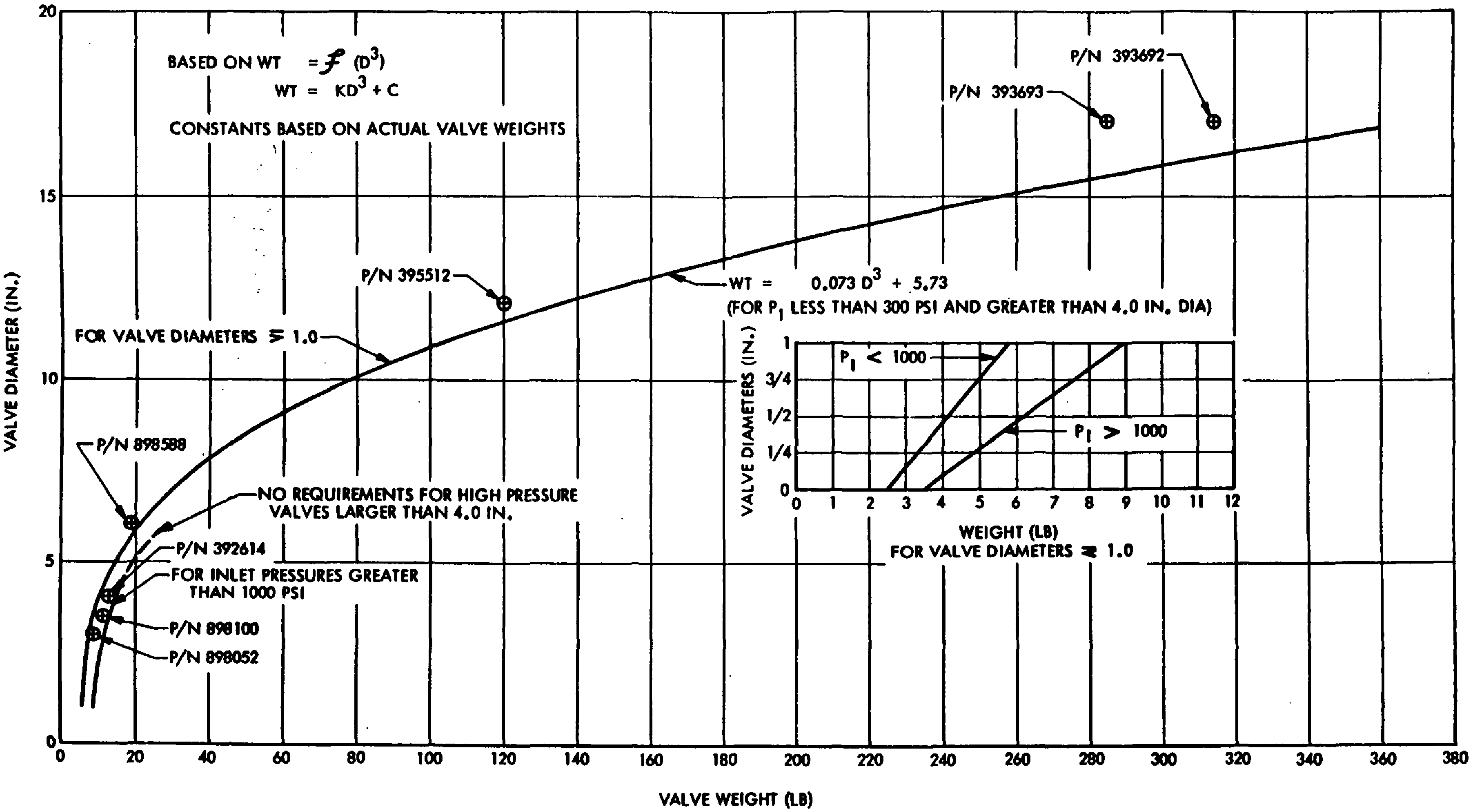

Fig. 11.1-4 Weight vs Valve Diameter (Estimated), Pressure Regulators, Flow Controls, Pressure Relief and Mix Valves, Butterfly Type

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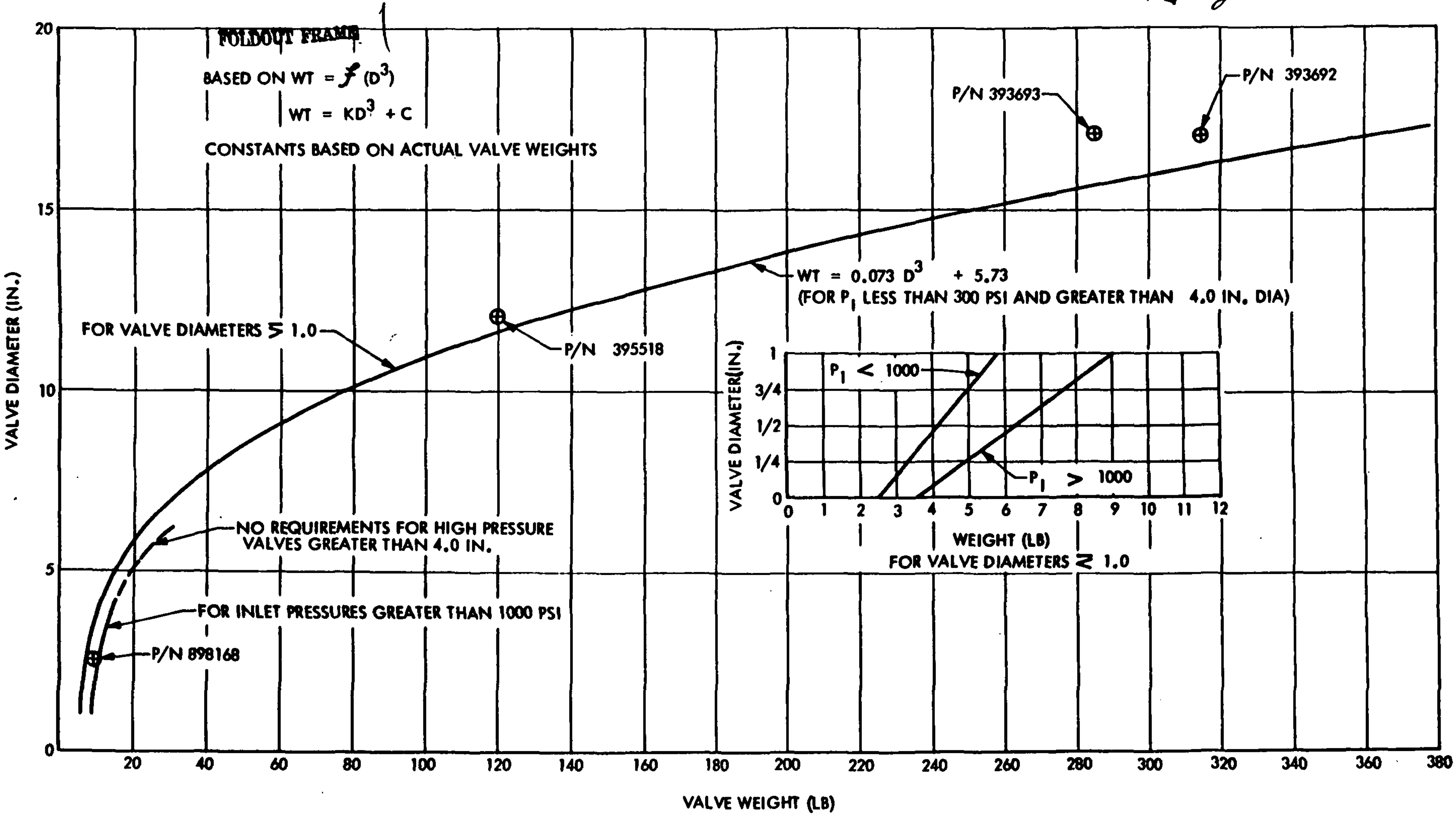

Fig. 11.1-5 Weight vs Valve Diameter (Estimated), Pressure Regulators, Flow Controls, Pressure Relief Valves, and Mix Valves, Poppet Type

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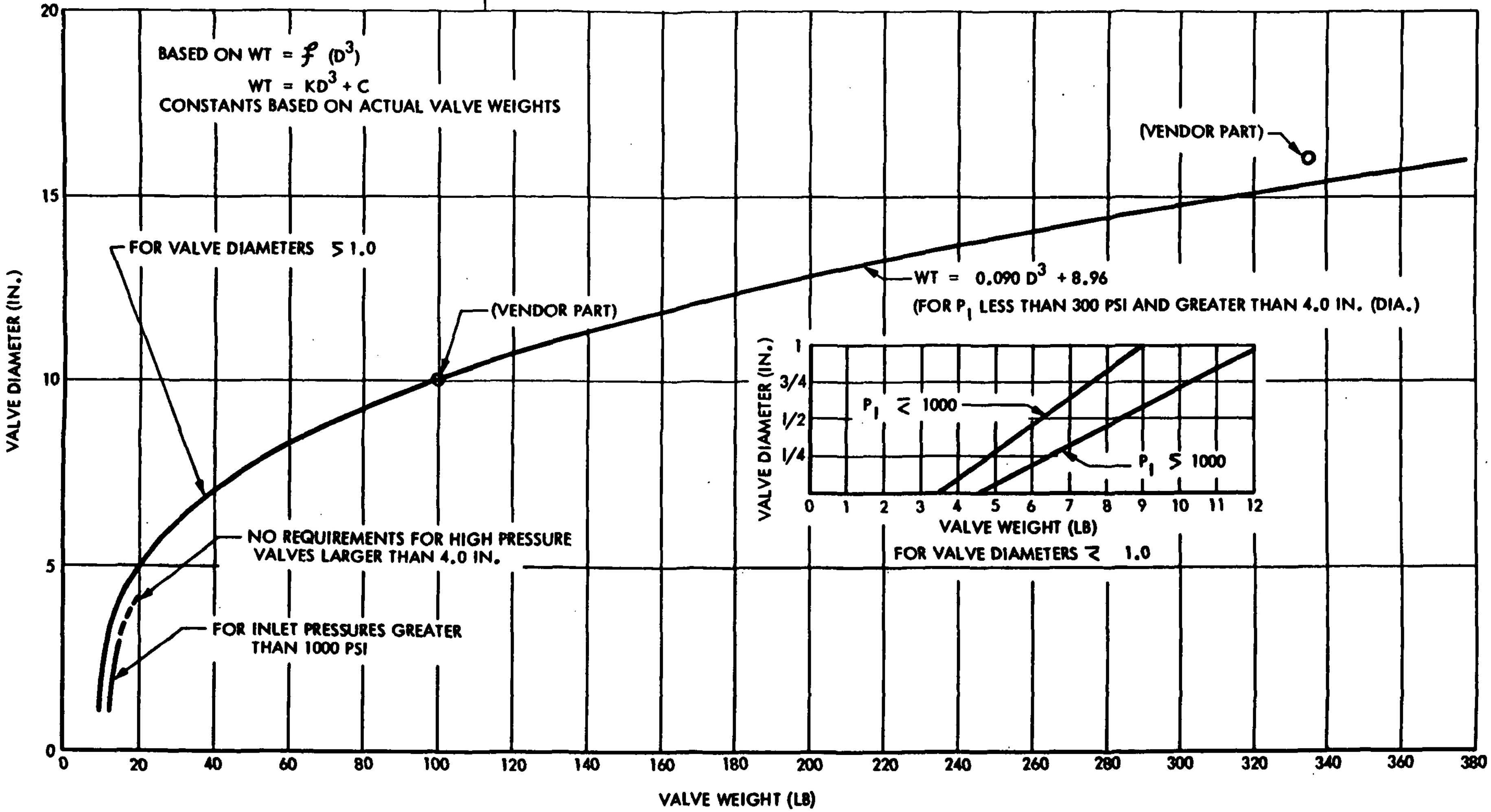

Fig. 11.1-6 Weight vs Valve Diameter (Estimated), Extra Heavy Solenoid and Ball Valves, Butterfly Type

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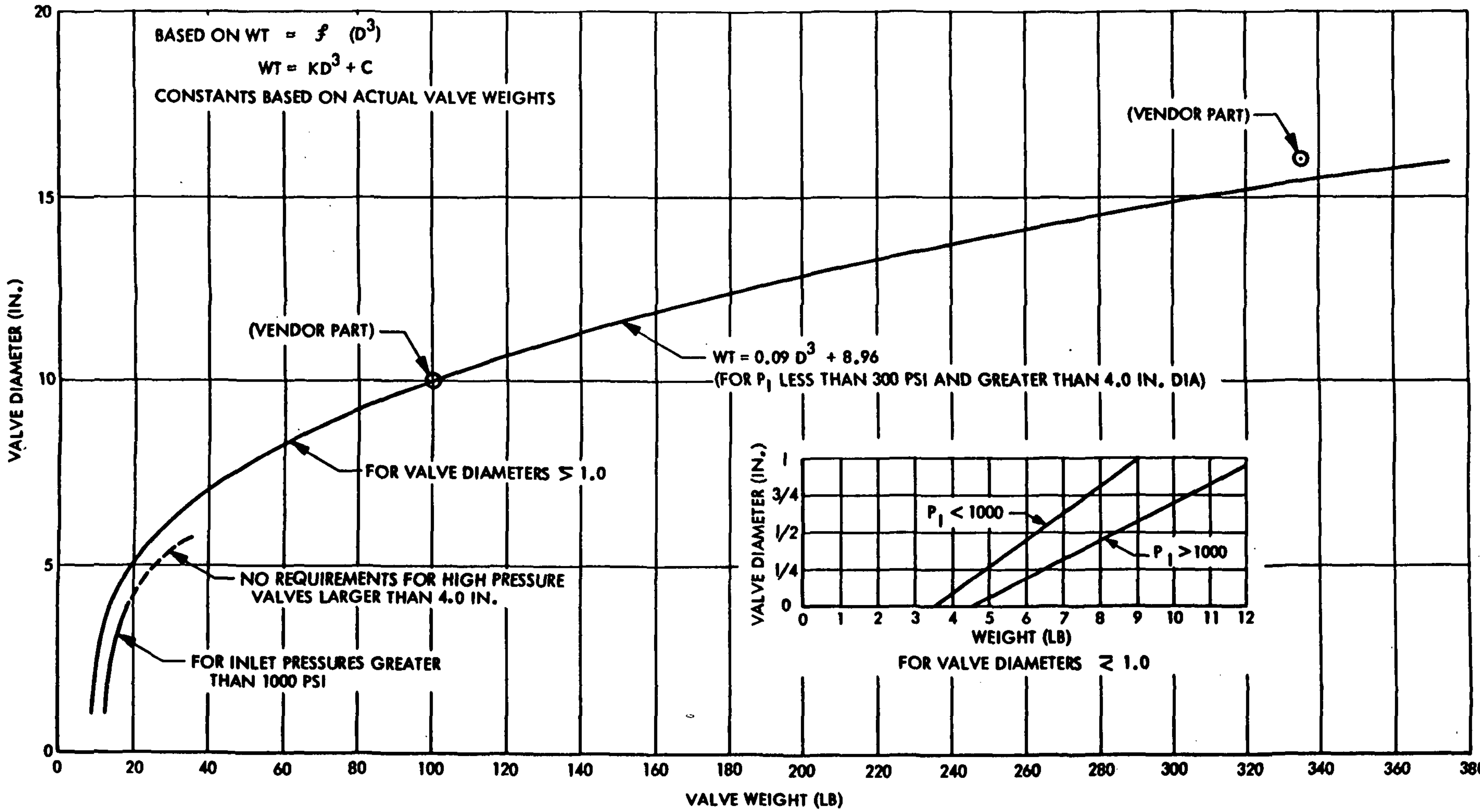

Fig. 11.1-7 Weight vs Valve Diameter (Estimated), Extra Heavy Solenoid and Ball Valves, Poppet Type

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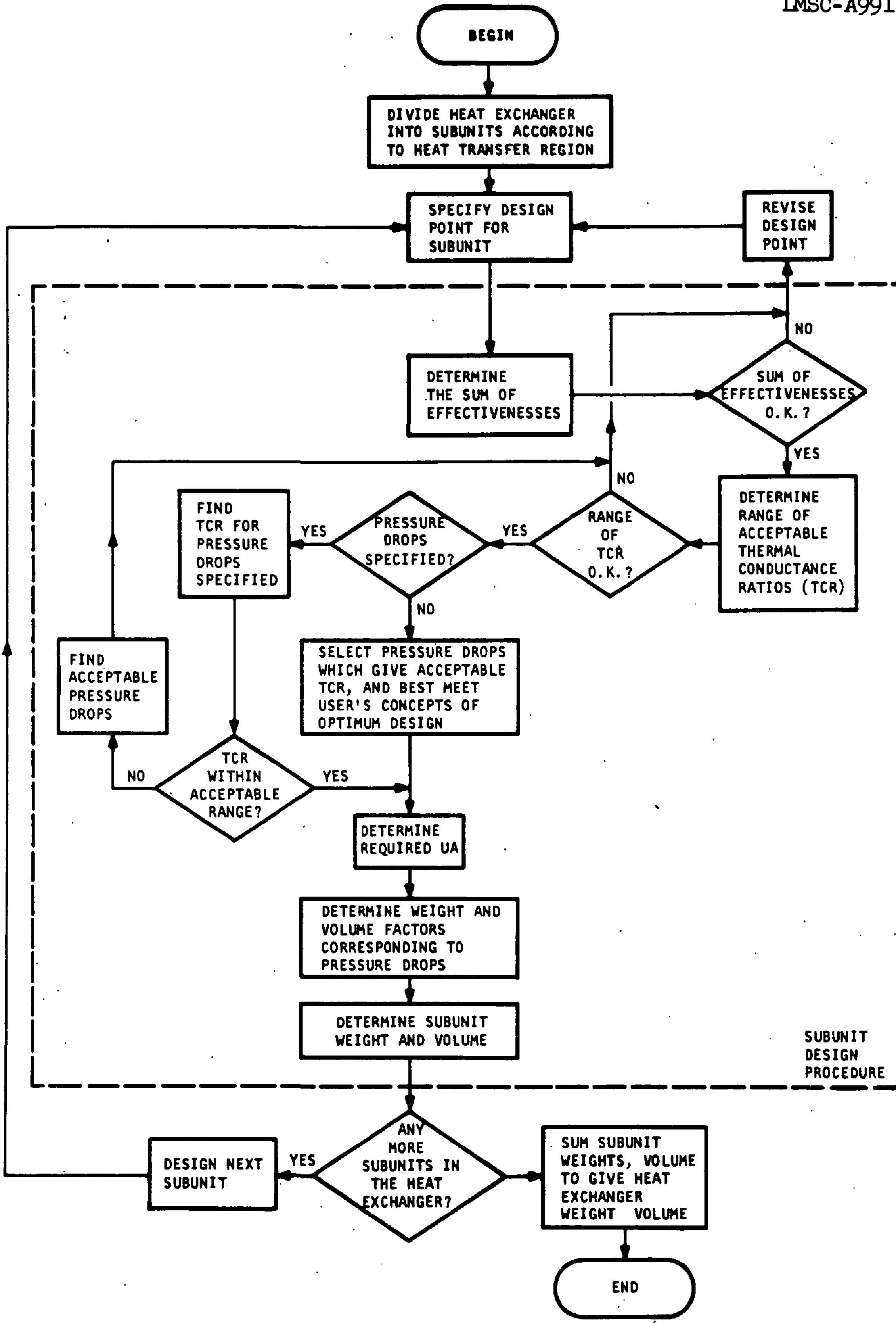

Fig. 11.1-8 Outline of Method Used for Determining Weight and Volume of Heat Exchangers

$P_{c,\ in}$ = Pressure of the cryogenic fluid at inlet

$T_{c,\ out}$ = Temperature of the cryogenic fluid at outlet

$T_{h,\ in}$ = Temperature of the combustion products at inlet

$P_{h,\ in}$ = Pressure of the combustion products at inlet

$T_{h,\ out}$ = Temperature of the combustion products at outlet

OF = Combustion products oxidizer-to-fuel ratio

The resulting approach is very extensive and can be found in the Shuttle Cryogenic Supply System Optimization Study Task Reports.

11.1.1.1.3 Pump Parametric Data. Pump parametric data were divided into two parts: design data and off-design data.

The design data enable the user to determine the following pump characteristics:

a. Length
b. Diameter
c. Volume
d. Weight
e. Efficiency
f. Power requirement
g. Rotational speed
h. Specific speed
i. Net Positive Suction Pressure (NPSP) requirement

Items a. through f. and i. are directly applicable to system studies, while Items g. and h. are presented for performance determination when pump-operating conditions are different than those for which the pump was designed.

The off-design data allow the estimation of pump performance, when it is operating at conditions other than those for which it was designed. Off-design efficiencies are principal outputs from these curves.

11.1.1.3 Summary of AiResearch Component Selection Results. The examination by AiResearch resulted in the specification of components for each application. For most of the valving, equivalent components were existing. Heat exchanger designs were within the state-of-the-art. Pump designs were specified, but it is known that pump development would be required for most of the applications.

11.1.2 Mechanical and Electrical Component Data Collection and Related Analyses

Lockheed engaged in supplemental component data collection and performed analyses relative to the selection of components.

11.1.2.1 Electrical Motors. As noted in the subsystem discussions, electrical motors offer potential for application to the following:

- Attitude Control Propellant Supply
  (1) Operation of boost pumps (if employed):
  LO_2 - 8 hp
  LH_2 - 33 hp

  (2) Operation of the ACPS pumps:
  LO_2 - 88 hp
  LH_2 - 405 hp

- Orbit Maneuvering Propellant Supply
  - (1) Operation of boost pumps (if employed):
    - LO_2 - 7.5 hp
    - LH_2 - 25 hp
  - (2) Operation of OMPS pumps:
    - LO_2 - 84 hp
    - LH_2 - 309 hp
  - (3) Feedline circulation pumps (if employed):
    - $\left.\begin{array}{l} LO_2 \\ LH_2 \end{array}\right\}$ - ~ 0.1 hp
  - (4) Circulating fans for thermal conditioning:
    - $\left.\begin{array}{l} LO_2 \\ LH_2 \end{array}\right\}$ - ~ 0.01 hp
- Auxiliary Power Unit Supply
  - (1) Operation of the APU pumps:
    - LO_2 - 4 hp
    - LH_2 - 63 hp
- Orbit Injection Propellant Supply
  - (1) Feedline circulation pumps:
    - LO_2 - 10-12 hp
    - LH_2 - 6-9 hp

The cryogenic cooling of an electrical motor gives definite advantages in the improvements in efficiencies. Possible types include:

- AC motors
- DC motors
- Brushless DC motors

11.1.2.1.1 AC Motors. Classification and performance characteristics of AC motors depend primarily on the electromagnetic construction of the rotor. When the rotor flux is generated by a voltage induced in the rotor by the changing stator flux, the motor is classified as an induction type. When the rotor flux is generated by DC excitation through a commutator or slip rings, or if the rotor is a permanent magnet, the motor is classified as a synchronous type.

The speed of a synchronous-type motor is directly proportional to the frequency of the AC-voltage excitation in the stator, whereas the speed of an induction-type is a function of the stator voltage magnitude in addition to the voltage frequency. Therefore, the inherent speed-regulation control of the synchronous-type motor is simpler and generally superior to that of the induction type.

Efficiencies of the two types of motors are not as closely comparable. The synchronous-type, due primarily to larger iron losses, generally operates with low efficiencies. Induction-type motors commonly operate with higher efficiencies. For this reason, the induction motor appears to be the most suitable AC type.

In an AC motor, a given magnetic circuit and winding is capable of a definite maximum torque. Since the iron magnetic saturation is clearly defined, increasing the flux density beyond saturation causes excessive magnetizing current and increased drain on the power supply.

An AC motor for cryogenic application has been developed; it is a 50-hp, two-pole induction motor, operated at 23,000 rpm on a 400-cps supply. The unit has a continuous rating of 1.8 hp/lb.

11.1.2.1.2 DC Motors. Conventional DC motors using graphite-impregnated brushes have had an inherent problem of short life in a space environment. When operated in a vacuum, graphite brushes have tended to flake and powderize - thus, reducing life. In recent years, developments have improved life; the conventional DC motor will function better in sealed and pressurized environments.

The brushless DC motor seems to be a promising DC motor type in the lower horsepower applications. These motors have essentially the same characteristics of conventional DC motors, but the problems associated with brushes are nonexistent.

Functions of the stator and rotor of a conventional DC motor are exactly reversed by the brushless DC motor; (i.e., the rotor maintains a constant flux from a permanent magnet, and the stator effectively produces a rotating flux wave through electronic commutation). Pairs of coils are located circumferentially around the axis of rotation, and the DC excitation is electronically switched to these coils in sequence producing the rotating flux. The DC switching is usually controlled photoelectrically by the rotor position.

Fractional horsepower, brushless DC motors are switched using transistors, but in the integral horsepower range, SCRs (Silicon Controlled Rectifiers) are required to switch the high currents. Speed regulation is accomplished by modulating the switched pulse width, thereby controlling the time that the flux field is maintained. Thus, brushless DC motor speed is sensitive to pulsing or quickly fluctuating-line inputs, while being relatively insensitive to slow-voltage decay. Because of the pulse width modulation technique of speed control, the motor draws current in pulses and, therefore, will require a filter network to dampen the current oscillations.

The efficiency of a brushless DC motor is good.

Since starting currents in a DC brushless motor are considerably higher than rated current, current limiting is required.

In a DC motor, the maximum torque capability is not as clearly defined as for the AC motor. If a higher torque load is applied, the machine will slow down, lowering the counter-emf and resulting in a higher current input. This produces a higher torque to equal the increased load.

DC motors have been operated in liquid hydrogen at 6 hp. The motors may achieve 1 hp/lb.

11.1.2.1.3 General Discussions Relative to AC Motors and DC Motors. Motor speeds and motor efficiencies may not be strongly related at the speeds under consideration. However, motor speed is related to weight. At higher speeds, less torque is required to generate an equivalent shaft output power.

Since torque dictates the size of the motor frame, it is also the principal factor governing weight. Then, a motor operating at high speed would weigh less than one delivering an equal output and operating at low speed.

Motor weight varies with output power at a given speed. The relationship is primarily a function of torque as described above.

Both AC induction and DC brushless motors can be speed-regulated $\pm$ 1 percent of the rated speed using temperature compensation techniques, and/or a frequency standard in the AC case. This corresponds to speed-torque characteristics where speed variations are held to within $\pm$ 1 percent over a range of torques. Speed control in a brushless DC motor is active; i.e., speed can be regulated relative to shaft speed or pump pressure by a feedback system. In an AC motor-inverter, speed control is usually passive.

Speed depends primarily on the inverter switching frequency, which is not usually actively controlled. Since speed-regulation circuitry operates at low-power levels, the added weight and power consumption for either motor are nearly constant over the motor power range. Speed-regulation provisions result in added circuit complexity and a smaller percentagewise change in overall efficiency and weight as larger motors are required.

Starting currents can be limited in both types of motors. However, current limiting may adversely affect the AC motor, depending on the initial load torque imposed. A centrifugal pump imposes a negligible initial load torque, while a positive displacement pump may impose an initial load torque as high as 50 percent of full load. This can cause the AC motor to partially stall and overheat, although not to the point of destruction. Nominal starting current for a noncurrent-limited AC motor is 500 percent of full-load current. At this current, approximately 200 percent of full-load torque is generated. If current is limited to 150 percent of full-load current, it is expected that starting torque will be only 60 percent of full-load torque. In a DC motor, the torque is directly proportional to current, and nonlimited starting currents are sometimes in the order of 20 times rated current. In order to protect the power source, current limiting is the normal method of operation.

Figure 11.1-9 grossly approximates the starting currents required to bring a brushless DC motor up-to-speed in a given increment of time. This plot indicates that the motor, driving a centrifugal pump, can require a very high current if starting times of less than 0.5 sec are desired.

The rotor of the brushless DC motor, being a permanent magnet, has a mass and moment of inertia much larger than that of an induction motor. While the larger mass tends to minimize and smooth speed fluctuations due to torque transients, it is anticipated that the starting time of the brushless DC motor would be somewhat greater than that of the induction motor.

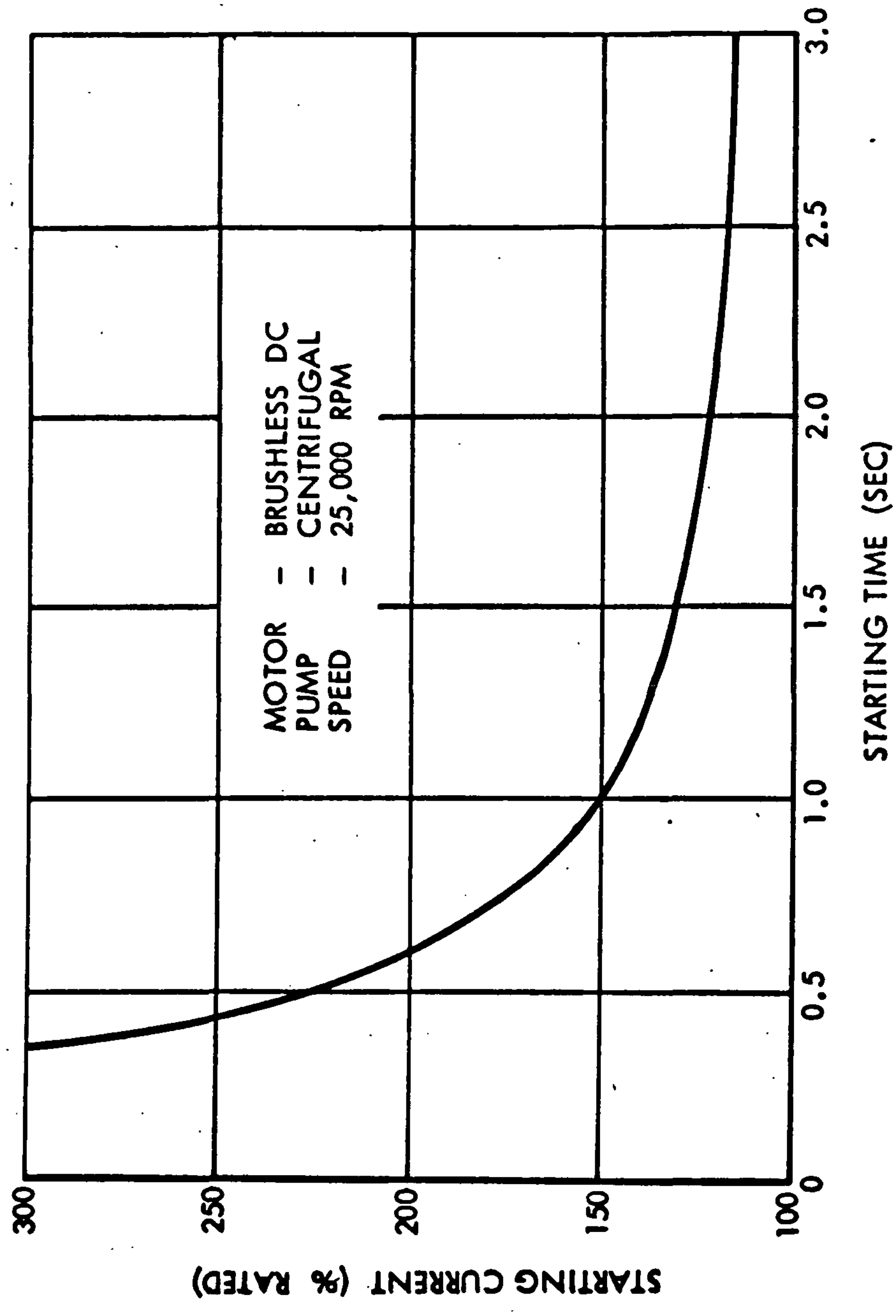

Fig. 11.1-9 Starting Current Requirements

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An AC induction motor-inverter will probably weigh more than a brushless DC motor. The efficiency of the brushless DC motor is at least equal to that of the induction motor-inverter and will probably exceed it. Additionally, the brushless DC motor offers better operation under current limited conditions.

Since torque is directly proportional to the current in the brushless DC type, less starting current is required to generate the same starting torque as in an AC type for which other factors come into play. The rotor of the brushless DC motor has a greater moment of inertia than the AC; the torque transients would cause less drastic changes in speed.

11.1.2.2 Thermal Conditioning Units. Existing Thermal Conditioning Unit (TCU) approaches such as those developed by LMSC in "Liquid Propellant Thermal Conditioning System", NAS 3-7942 and NAS 3-12033, as shown in Fig. 11.1-10, are applicable to the requirements generated in this study.

One of the principal considerations in the TCU application has been the method of controlling venting. These venting considerations are as follows:

- Venting to control the vapor pressure of the liquid hydrogen in the hydrogen-storage tanks

    (1) Control potentially by tank pressure or by temperature

- Venting of hydrogen to control the vapor pressure in the liquid-oxygen tanks

    (1) Hydrogen vented on demand and used to cool the liquid-oxygen tanks

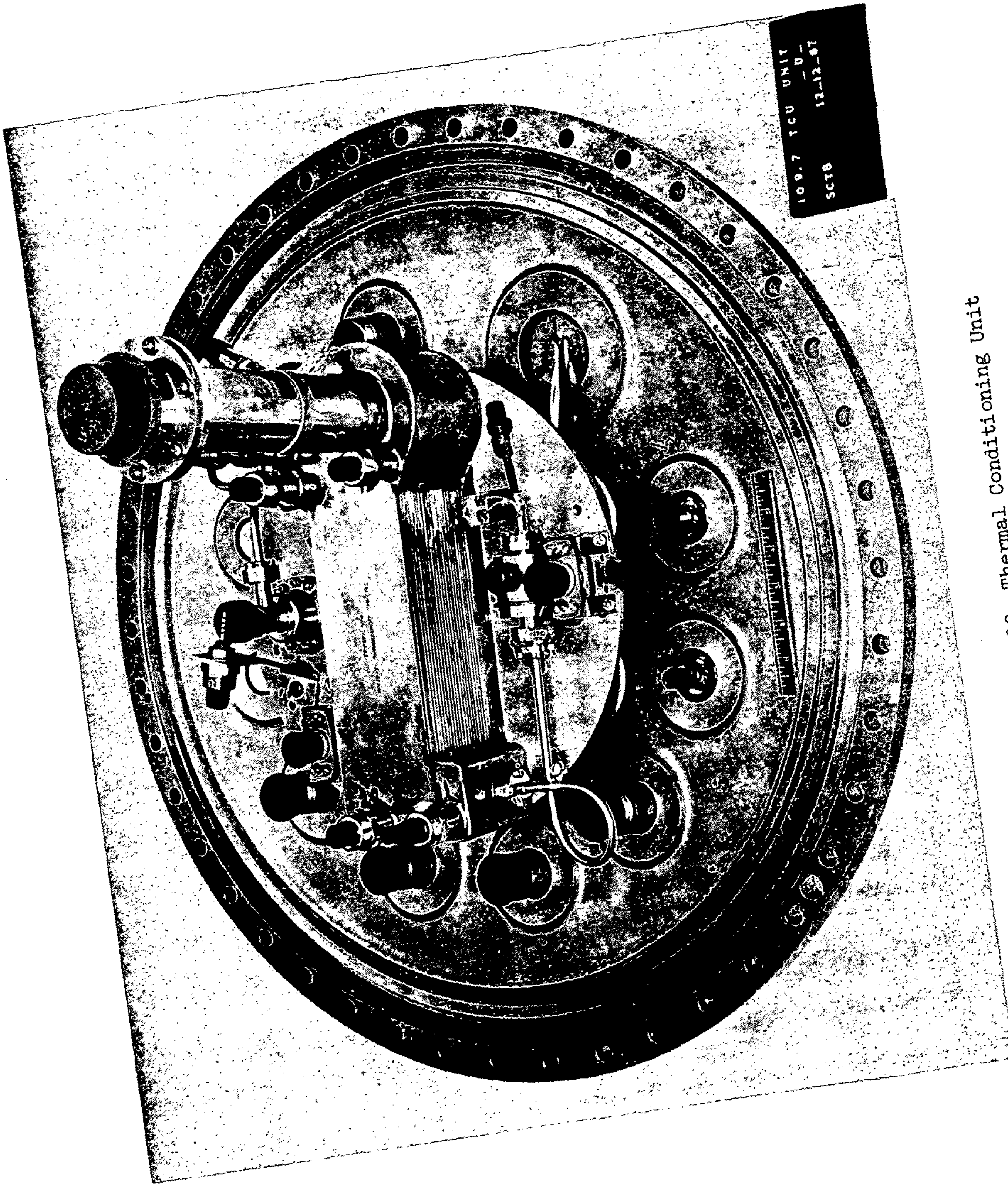

Fig. 11.1-10 Thermal Conditioning Unit

(2) Hydrogen-tank venting by temperature or pressure in the liquid-oxygen tank

- Venting of hydrogen to provide cooling to pumps, lines, or other equipment requiring cooling

    (1) Venting controlled by the temperature of the equipment being conditioned

11.1.2.2.1 <u>Venting to Control the Vapor Pressure of the Liquid Hydrogen (or Liquid-Oxygen) Tanks</u>. Heat addition to the liquid-hydrogen tanks (or the liquid-oxygen tanks) by any means, such as heat leak through the insulation or structure, results in an increase in the liquid temperature and subsequently the vapor pressure. The increase in vapor pressure results in a corresponding increase in tank total pressure, regardless of whether the tank is pressurized by helium or only has the propellant gases pressurizing the tanks.

In the OMPS/ACPS integrated systems, or any other subcritical system requiring instant start, the tank pressure must be kept up to a given total pressure and a given NPSP (total pressure - vapor pressure). This may be controlled by a pressure switch, which opens the valves, or by a regulator; either control admits helium to keep the pressure at the desired level.

If tank pressure is used as the indicator of vapor pressure rise, then any tank pressure over and above a given value will be interpreted as liquid-hydrogen (or liquid-oxygen) vapor pressure rise, and the TCU will withdraw liquid, expand this, and run it through the heat exchanger to cool the liquid and reduce the vapor pressure. The problem with this type of control is that any pressure rise is interpreted as a need for venting.

If the pressure rise is due to some other factor, the hydrogen is needlessly vented and subcooled. For example, helium leakage into the tank, if sufficiently large, can raise the pressure and be interpreted as a signal to lower the vapor pressure. Likewise, during a rapid withdrawal of liquid, such as during an engine burn, some liquid subcooling occurs. However, the tank pressure is being kept up to a desired level by helium addition. When heat is subsequently added to the tanks, the vapor pressure rises, and if pressure control is being used, venting automatically occurs. Through a succession of OMPS engine burns, or ACPS operations, the vapor pressure (temperature) of the liquid can be driven down needlessly.

The conclusion from these considerations is that if an effective liquid-hydrogen venting system could be controlled by temperature, then the vapor pressure could be accurately controlled. Liquid-hydrogen demand venting for liquid-oxygen vapor pressure control could be by the same approach. The control system would be provided with an accurate indication of the vapor pressures within the liquid-hydrogen and liquid-oxygen tanks, which would be desirable for monitoring purposes. It would be desirable to obtain temperature-sensing accurate within $\pm$ 0.1°R, but up to $\pm$ 0.5°R could probably be accepted.

If hot gas pressurization were being employed, the sensors would be appropriately disabled until equilibrium conditions were restored. As discussed elsewhere in the report, under certain conditions, it is desirable to vent hot gases used for pressurization during shutdown to remove this heat from the propellant tanks.

11.1.2.3 Instrumentation Components. Both Lockheed and AiResearch produced inputs to the instrumentation components. The Instrumentation and Control subsystem analyses are presented in Appendix D. A discussion of these components follows.

- Pressure Switches - For most tank applications, AiResearch selected a bellows-type switch; possible alternative is the metal diaphragm-type switch. For application in lines, a belleville spring-type switch was selected.

- Pressure Transducers - The pressure transducers only operate satisfactorily in the gaseous or supercritical conditions. A variable reluctance-type transducer was selected.

- Temperature Transducers - A variety of temperature transducers could have been selected. The precision platinum-type transducer is satisfactory for the applications.

- Point Level Sensors - The optical-type point level sensor has been increased in ruggedness in the last few years and is, by far, the most accurate point level sensor. An alternative to this is the use of the capacitance-type point level sensors.

11.1.2.3.1 Continuous Liquid-Level Indicators. There have been no firm requirements generated in the study for zero-gravity sensing devices. The continuous level sensor, therefore, could be the capacitance-type with concentric tubes.

Zero-gravity devices were examined in the course of the study. The general conclusion was that the Radio Frequency Gaging Technique and the Nucleonic Gaging Techniques are both promising systems. The Radio Frequency Gaging Technique will produce better results with oxygen and storable propellants than with hydrogen. The mode count is much more definitized in oxygen.

11.1.2.3.2 Control Units. AiResearch provided descriptions for the control units for the applications in the subsystems. Each of these was discussed specifically for the applications. The data sheets for these components

are presented in the Task Reports.

11.1.3 Leakage Analyses. The leakage of gas through valves and regulators is considered to be an inherent characteristic of the components. However, the leakage of liquid is considered to be related to a failure, with the exception of disconnects. The possible occurrences and effects from component leakage, which were considered significant, were:

- Liquid Hydrogen
  (1) Leakage of LH_2 or GH_2 in the atmosphere resulting in a potential fire or explosion hazard
  (2) Leakage of GH_2 (and GHe) into insulation systems or vacuum jackets resulting in performance degradation
  (3) Leakage of GHe into tanks resulting in overpressurization
  (4) Leakage of GHe from tanks resulting in helium loss
  (5) Significant loss of propellant or reactant occurring from leakage

- Liquid Oxygen
  (1) Leakage of LO_2 or GO_2 onto organics resulting in a potential fire hazard
  (2) Leakage of GO_2 (and GHe) into insulation systems or vacuum jackets resulting in performance degradation
  (3) Leakage of GHe into tanks resulting in overpressurization
  (4) Leakage of GHe from tanks resulting in helium loss
  (5) Significant loss of propellant or reactant occurring from leakage

11.1.3.1 Leakage of Liquid Hydrogen or Liquid Oxygen. The leakage of liquid hydrogen or liquid oxygen is considered only to be possible in the case of component failure. Fail-operational/fail-safe provisions should be arranged and instrumented to handle this type of failure.

11.1.3.2 Leakage of Gaseous Hydrogen into the Atmosphere. It must be considered that the leakage of any amount of gaseous hydrogen into the atmosphere presents a possible ignition source. Hydrogen leakage on the order of 10-to-100 sccm has been observed to support combustion under controlled conditions. To date, LMSC has not located sufficient data relating to sustaining of flames of hydrogen in air. The information required must relate low flowrates (sccm) to opening sizes and air movement for the sustaining of flames.

11.1.3.3 Leakage of Propellants and Reactants. Leakage can result in the loss of propellants and reactants. However, when this is analyzed for the shuttle systems, it is found that leakages must be extremely high (high enough to be in the failure range) before significant losses of propellants and reactants will occur.

11.1.3.4 Leakage of Helium from Propellant and Reactant Tanks. Helium requires a high weight for storage, and its leakage from helium-pressurized tanks can result in weight penalties. Analyses were made considering the combined leakage rate of the propellant gases with helium. Cases were selected that were considered representative of the subcritical systems. The resulting helium losses from oxygen and hydrogen tanks as a function of the leakage rates are presented in Figs. 11.1-11 and 11.1-12, respectively. As noted from these curves, (1) the leakage rates must be relatively high in order to leak a significant amount of helium, and (2) for a given leakage rate, the helium loss from a LO_2 tank is greater than the loss from a LH_2 tank.

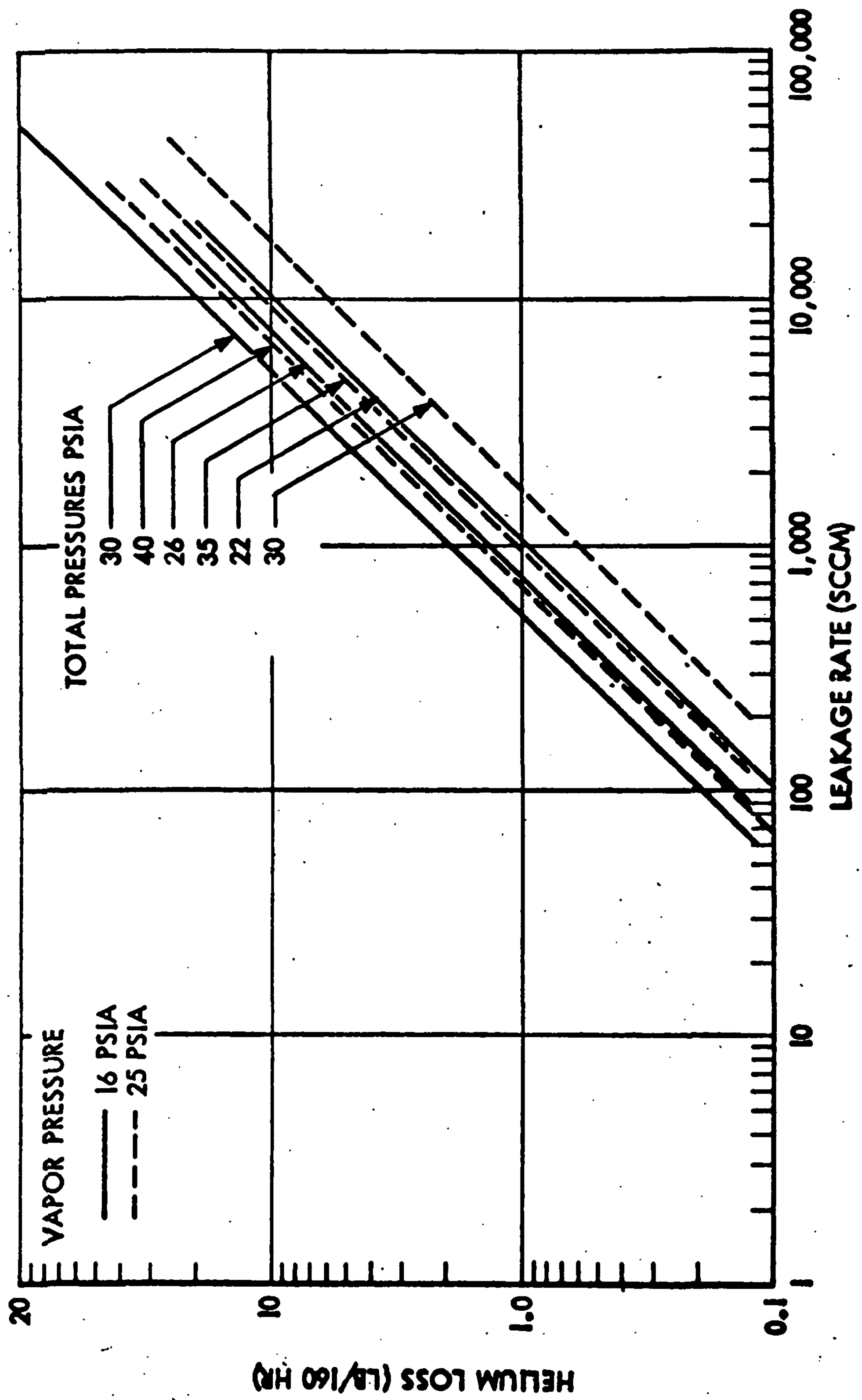

Fig. 11.1-11 Helium Loss From Liquid-Oxygen Tanks

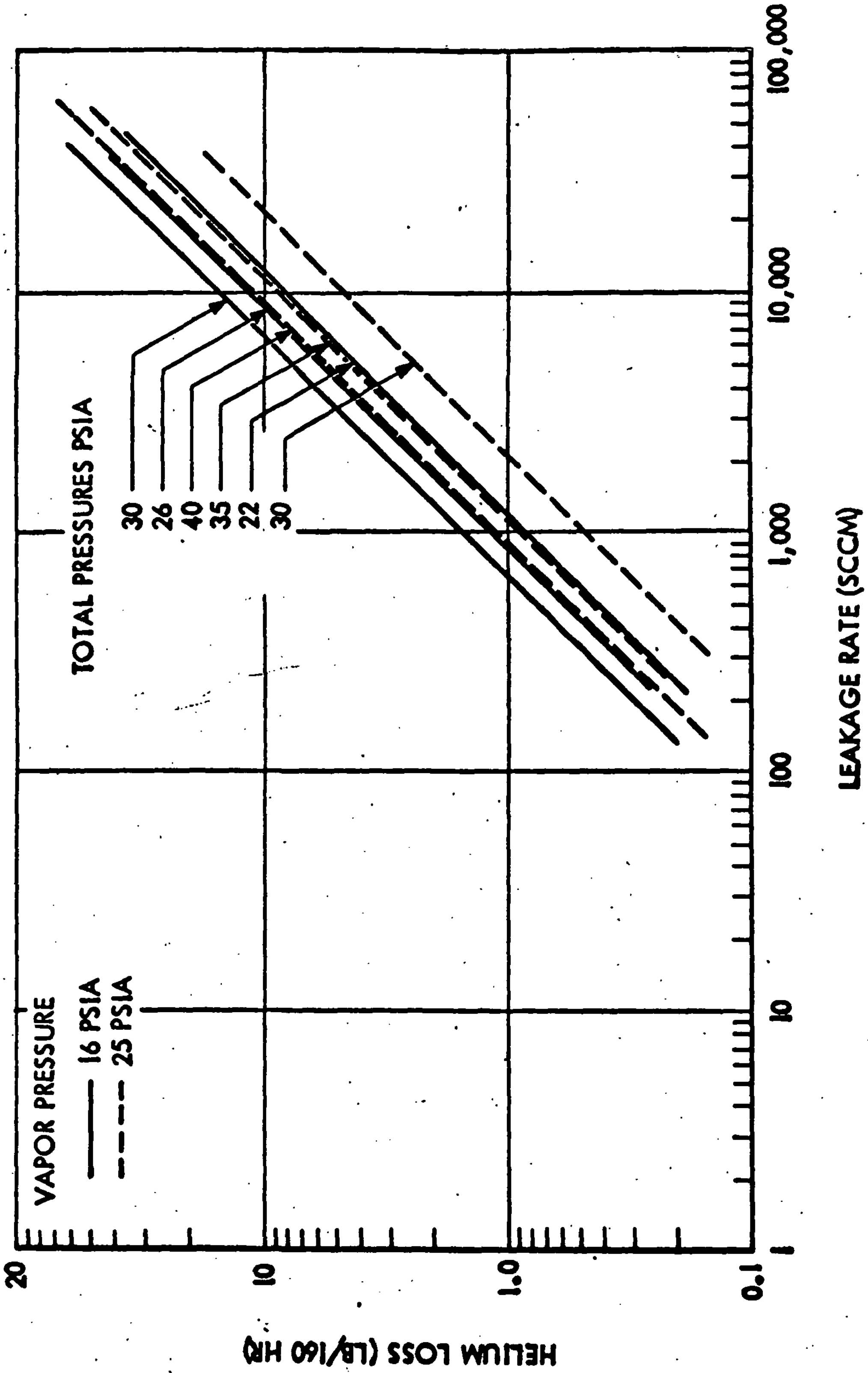

Fig. 11.1-12 Helium Loss From Hydrogen Tanks

11.1.3.5 Tank Pressure Rise from Helium Leakage. The tank pressure rise in propellant and reactant tanks from helium leakage into the tanks can possibly result in overpressurization. Also, it can result in the signaling of TCUs to vent and cool hydrogen unnecessarily. Parametric data are presented in Figs. 11.1-13 and 11.1-14 regarding helium leakage into oxygen and hydrogen tanks. Data presented in these curves cannot be applied directly to a given tank, but do indicate the maximum conditions.

Additional studies were made using the Orbit Maneuvering Propellant Tank with integrated Attitude Control Propellant Supply; a typical duty cycle for propellant withdrawal was used. The results are presented in Fig. 11.1-15. Note that the liquid-oxygen tanks could have significant pressure rises. Liquid-hydrogen tank pressure rises are relatively low.

11.1.4 Tankage Data Collection

Extensive parametric tank data were collected in order to support the tradeoff studies and to provide data for future analyses.

11.1.4.1 Metallic Tankage. In performing the Reusable Subsystem Design Analysis, Contract No. FO 4 (611)-69-C-0041, LMSC conducted an extensive literature search regarding fracture mechanics and the reusability of shuttle tankage. One result of these analyses was that sustained pressure loading was the major degrading factor for propellant and reactant tanks, since the number of cycles is not the limiting factor. Accumulators require more pressure cycles, and cycling can become the limiting factor. From examination of available data, a Safety Factor of 2.0 was selected. Nonoptimum factors also were employed of 10 or 20 percent, depending upon the application.

Tank sizing was performed by computer programming. The program considered the liquid hydrostatic head, ullage pressure, and temperature characteristics, and determined the maximum condition. The principal comparisons are the

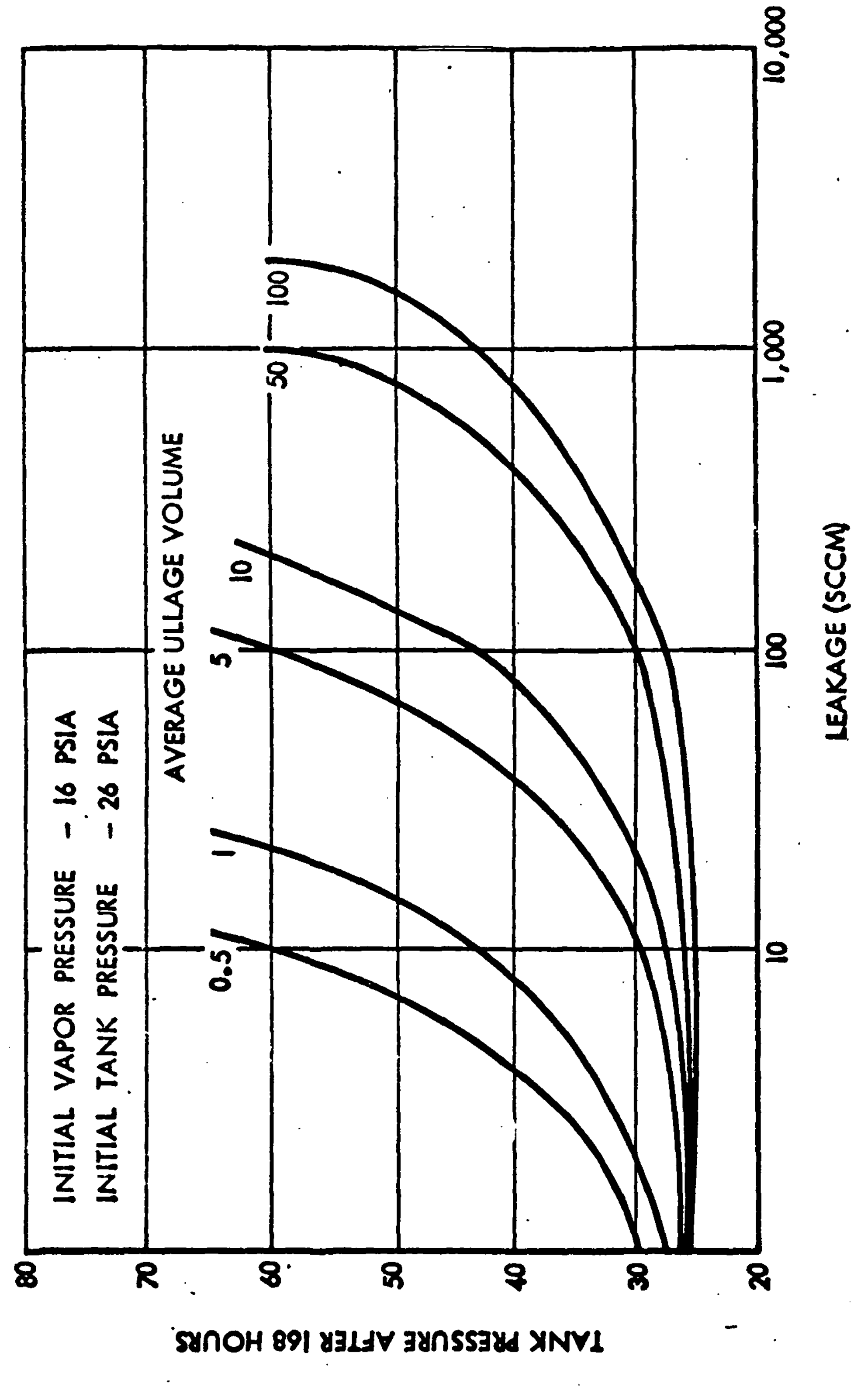

Fig. 11.1-13 Liquid-Oxygen Tank Pressure Rise From Helium Leakage

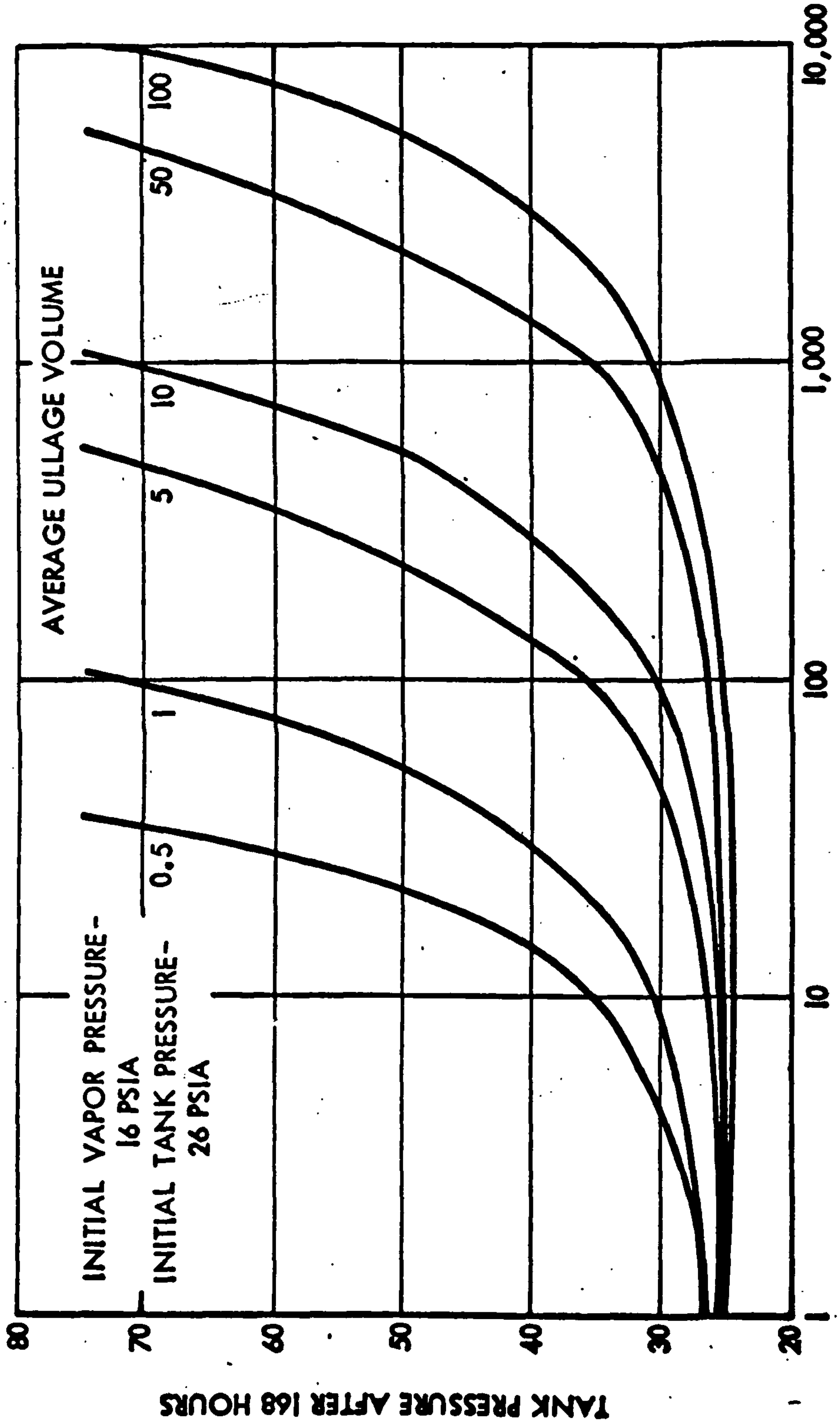

Fig. 11.1-14 Liquid-Hydrogen Tank Pressure Rise From Helium Leakage

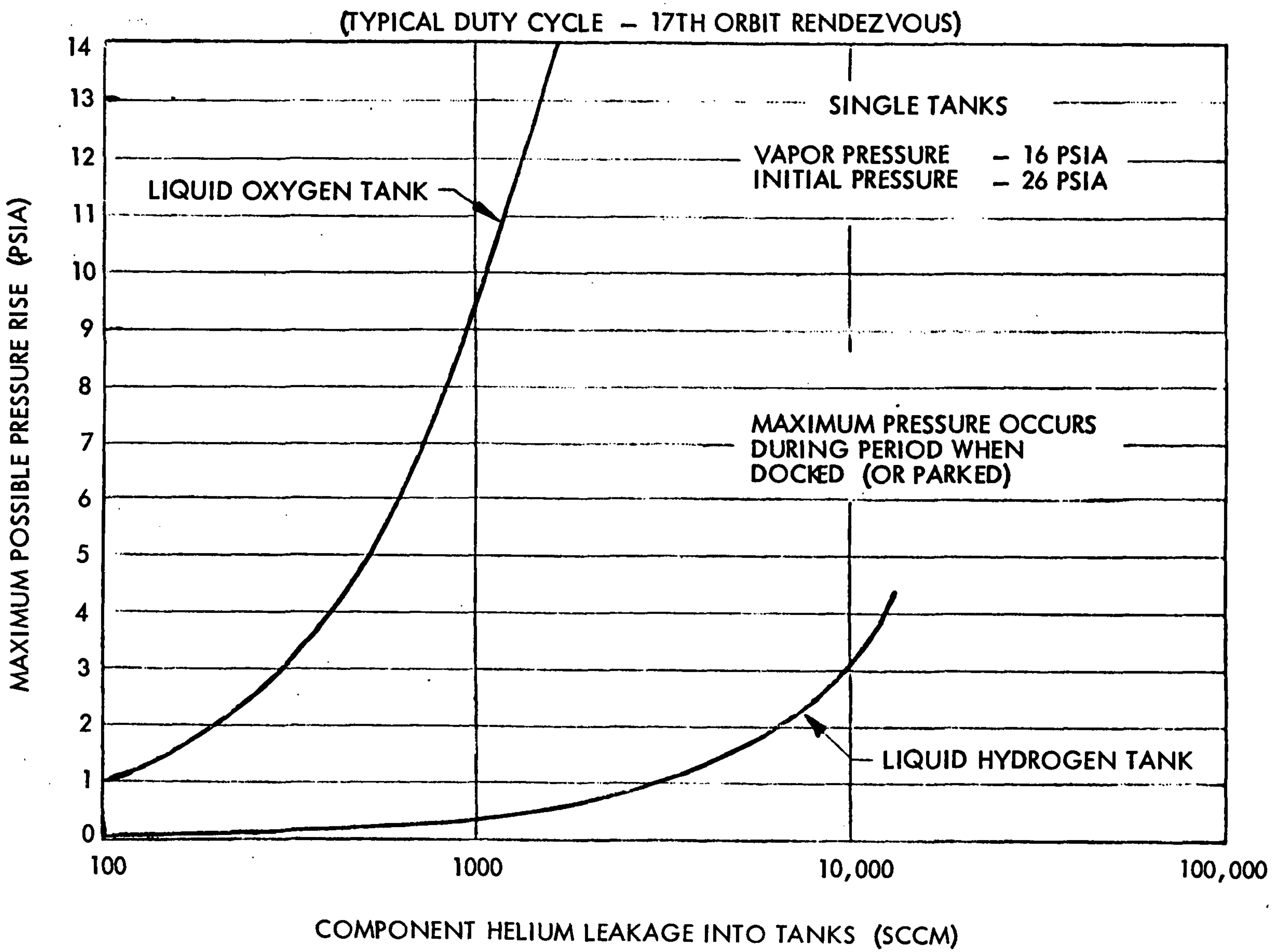

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Fig. 11.1-15 Effect of Helium Leakage into Tanks With Integrated OMPS/ACPS Propellants

fully loaded under peak 3-g acceleration to on-orbit or reentry mode with associated temperatures.

The tankage for which parametric data were produced is shown in Table 11.1-3.

11.1.4.2 Composite Tankage. Metal shells with an overwrapped glass-filament shell for high pressure storage make possible lighter weight tankage than homogeneous metal pressure vessels. Very high strength-to-density ratios are attainable.

The use of cryogenically formed stainless-steel tanks (Arde process) can potentially increase the advantages of composite tanks. These are stainless-steel 301 tanks. This material is satisfactory for reusable applications for oxygen at any temperature. However, prolonged storage of hydrogen at supercritical temperature can result in hydrogen embrittlement.

Table 11.1-3

SCOPE OF TANKAGE PARAMETRIC DATA

SYSTEM	TEMP. °F FROM	TO	PRESS. PSIG FROM	TO	DIAM. IN. FROM	TO	GEOM.	MAT'LS.
EC/LSS-SUBCRIT	-320	-280	75	150	0	40	SPHERE	2219-T87 AL
EC/LSS-SUPERCRIT	-320	-280	100	900	0	48	SPHERE	2219-T87 AL
EC/LSS-LN_2 SUPERCRIT	-320	-280	100	900	0	48	SPHERE	6AL-4V E.L.I.Ti
FUEL CELL-LH_2 (SUBCRITICAL)	-423	-423	60	120	30	50	SPHERE	2219-T87 AL
FUEL CELL-LO_2 (SUBCRITICAL)	-300	-300	60	120	30	50	SPHERE	2219-T87 AL
FUEL CELL - LO_2 (SUPERCRITICAL)	-290	+70	900	900	30	50	SPHERE	2219/321
FUEL CELL - LH_2 (SUPERCRITICAL)	-420	-260	375	375	30	50	SPHERE	2219/321 AND 6AL-4VE LI
FUEL CELL - LO_2	-406 SUBCRIT		120 SUBCRIT		20	60	SPHERE	2219/321
(SUB AND SUPERCRIT)	+ 15 SUPERCRIT		900 SUPERCRIT					
FUEL CELL - LH_2	-250 SUBCRIT		120 SUBCRIT		20	80	SPHERE	2219/321
(SUB AND SUPERCRIT)	-345 SUPERCRIT		375 SUPERCRIT					

Table 11.1-3 (CONT'D)

SCOPE OF TANKAGE PARAMETRIC DATA

SYSTEM	TEMP. °F FROM	TO	PRESS. PSIG FROM	TO	DIAM. IN. FROM	TO	GEOM.	MAT'LS.
APU - LH_2	-423	SUBCRIT	40	SUBCRIT	40	120	SPHERE	2219/321
(SUB AND SUPERCRITICAL)	-415	SUPERCRIT	350	SUPERCRIT				
APU - LO_2	-295	SUBCRIT	40	SUBCRIT	20	40	SPHERE	2219/321
(SUB AND SUPERCRITICAL)	-190	SUPERCRIT	940	SUPERCRIT				
OIS - LO_2	-297	-297	25	25	20	80	CYL+H-SPH	2219-T87
EXT JACKET - LH_2	+70	+70	1	1	162.8	166.8	CYL+H-SPH	2219-T87
OMS - LO_2	-295	-295	20	50	60	150	SPHERE	2219-T87
OMS - LH_2	-423	-423	20	20	80	160	CYL+H-SPH	2219-T87
OMS - LH_2	-423	-423	28	28	80	160	CYL+H-SPH	2219-T87
OMS - LH_2	-423	-423	35	35	80	160	CYL+H-SPH	2219-T87
OMS - LO_2	-130	-130	50	50	80	160	CYL+H-SPH	2219-T87
OMS - LH_2	-260	-260	35	35	80	160	CYL+H-SPH	2219-T87
ACPS - LH_2 (SUBCRITICAL)	-269	-269	22	22	60	100	SPHERE	2219-T87
ACPS - LH_2 (SUPERCRITICAL)	-110	-110	600	1000	60	100	CYL+H-SPH	2219-T87
ACPS - LH_2 (SUPERCRITICAL)	-110	-110	600	1000	60	100	CYL+H-SPH	TYPE 321/347
ACPS - LO_2 (SUBCRITICAL)	-205	-205	20	20	40	72	SPHERE	2219-T87
ACPS - LO_2 (SUPERCRITICAL)	+60	+60	1000	1000	80	140	CYL+H-SPH	2219/321

Table 11.1-3 (CONT'D)

SCOPE OF TANKAGE PARAMETRIC DATA

SYSTEM	TEMP. °F FROM	TO	PRESS. PSIG FROM	TO	DIAM. IN. FROM	TO	GEOM.	MAT'LS.
A C P S - LH_2	-421	-421	20	20	100	160	CYL+H+SPH	2219-T87
A C P S - ACCUM	-110	-110	600	1000	30	70	SPHERES	2219-T87
A C P S - ACCUM	-110	-110	600	1000	30	70	SPHERES	TYPE 321/347 S.S
ACCUM. - GAS	-423	-423	2000	4500	30	70	SPHERES	2219-T87 AL
ACCUM. - GAS	-297	-297	2000	4500	30	70	SPHERES	2219-T87
ACCUM. - GAS	+ 40	+ 40	2000	4500	30	70	SPHERES	2219-T87
ACCUM. - GAS	+200	+200	2000	4500	30	70	SPHERES	2219-T87
ACCUM. - GAS	-423	-423	2000	4500	30	70	SPHERES	321/347
ACCUM. - GAS	-297	-297	2000	4500	30	70	SPHERES	321/347
ACCUM. - GAS	+ 40	+ 40	2000	4500	30	70	SPHERES	321/347
ACCUM. - GAS	+200	+200	2000	4500	30	70	SPHERES	321/347
ACCUM. - GAS	-423	-423	2000	4500	0	95	SPHERES	6 AL-4V E.L.I.
ACCUM. - GAS	+ 60	+ 60	2000	4500	0	95	SPHERES	6 AL-4V E.L.I.

N/A ~ NOT APPLICABLE

L^1 ~ LIMIT MAX OPERATING PRESSURE

L^2 ~ EXTERNAL LIMIT COLLAPSE PRESSURE

11.1.5 Feedline Components Data Collection

Extensive contact with suppliers was employed in order to obtain feedline component data. Names of contributing suppliers are presented in Section 12.

11.1.5.1 Feedlines. One of the principal issues related to feedlines is the comparison of aluminum and stainless-steel feedlines. Parametric feedline data were generated for aluminum and stainless-steel feedlines as a function of pressure. An example of these data is presented in Fig. 11.1-16.

Aluminum feedlines can result in significant weight savings. However, aluminum expansion joints are not considered to be satisfactory. This would require transition joints to bellows of stainless steel or Inconel.

Transition pieces have been successfully fabricated and tested for diameters up to 10 inches, and have been satisfactorily tested for cryogenic applications, vacuum-holding capability (1×10^{-11} torr) and leakage rates (1×10^{-9} sccs).

There is sufficient evidence to assure that feedlines up to 18 inches are feasible. It is recognized that aluminum is more difficult to weld than stainless steel.

Vacuum-jacketed feedlines could be constructed to maintain vacuum conditions for extremely long periods (years). However, the major weakness in the system is the vacuum.

Vacuum sealoff valves are currently being made with Kel-F double seats. These seats are affected by the cryogenic temperatures and have a history of leakage. The Kel-F will gradually assume a compression set, and leakage probability is increased. Additional technology development is needed to improve the seals in the vacuum sealoff valves.

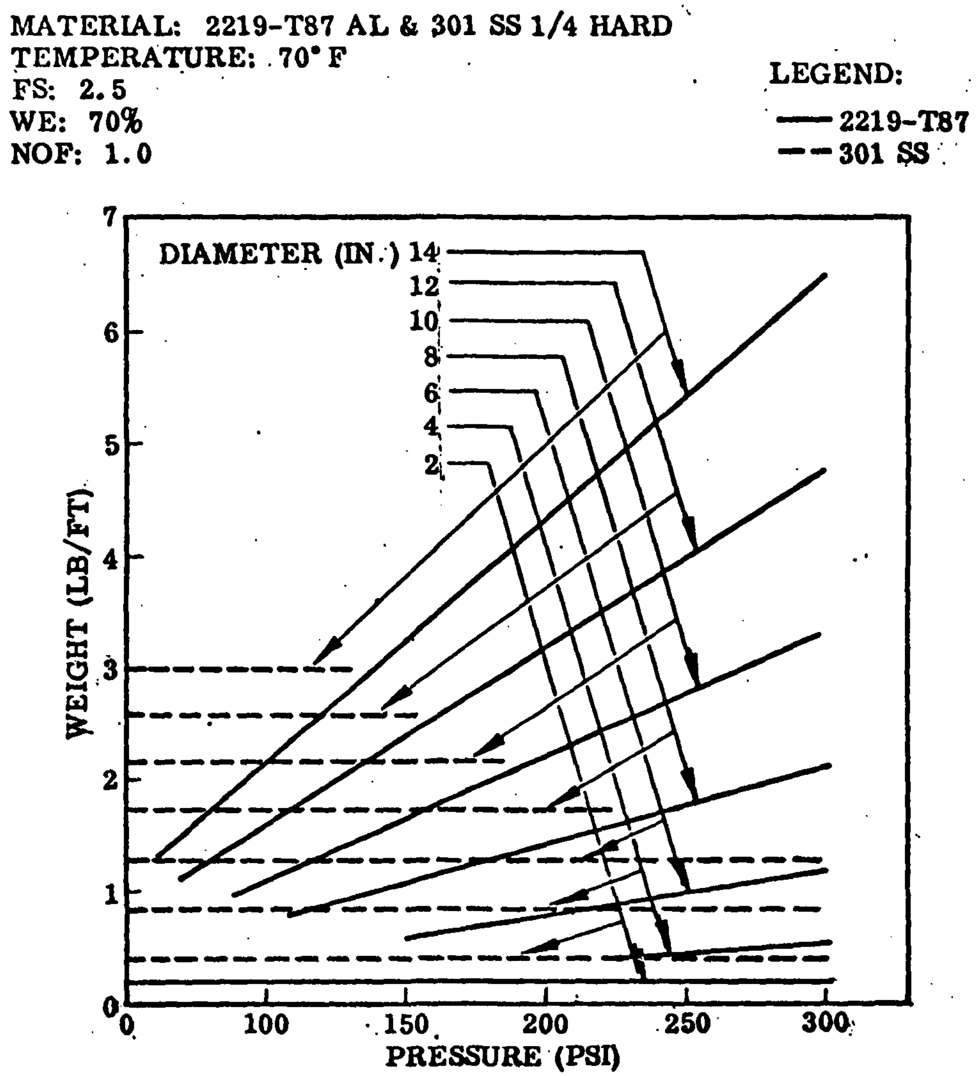

Fig. 11.1-16 Stainless Steel and Aluminum Feedline Weights

The vacuum-sensing tubes have a less severe leakage history, but the connector reliability and service-life definition needs to be improved. Heater wires on these probes should be removed and self-heating by the high-frequency technique should be employed. This has worked very well on the Saturn V systems.

Parametric vacuum-jacketed line data are presented in Fig. 11.1-17.

11.1.5.2 Feedline Components. Bellows segments, which during operation compensate for the thermal contraction and expansion of the lines, most likely should be fabricated from Inconel 718 or a 300 series stainless steel. The suppliers with experience in forming aluminum bellows were contacted for information, and they recommended against the use of aluminum in propellant feedlines because of the unreliable fatigue life.

The line design could be a basic tension system utilizing restrained expansion devices to facilitate line contraction and expansion during operation. Parametric data regarding bellows are presented in Figs. 11.1-18 through 11.1-21. As shown in the curves, the internal tierod bellows generally is the most desirable from a weight standpoint. However, since the internal yoke or tierod is in the flowstream, this bellows contributes to greater line losses than internally gimballed bellows; this is shown on the "Bellows K Factor Design Curves", Fig. 11.1-22. Externally gimballed bellows would have approximately the same "K" factor as a straight convoluted section. An even lower "K" factor can be obtained with the use of flow sleeves in the convoluted sections. Also, this type of bellows may contaminate the flowstream.

Contraction and expansion of the smaller diameter lines (1-in. diameter and smaller) will be taken care of by the line routing. The loads and stresses involved are small in magnitude and will not need expansion devices, except when the line interfaces with the engine; then gimballing devices will be used. Off-the-shelf bellows are not considered to be available.

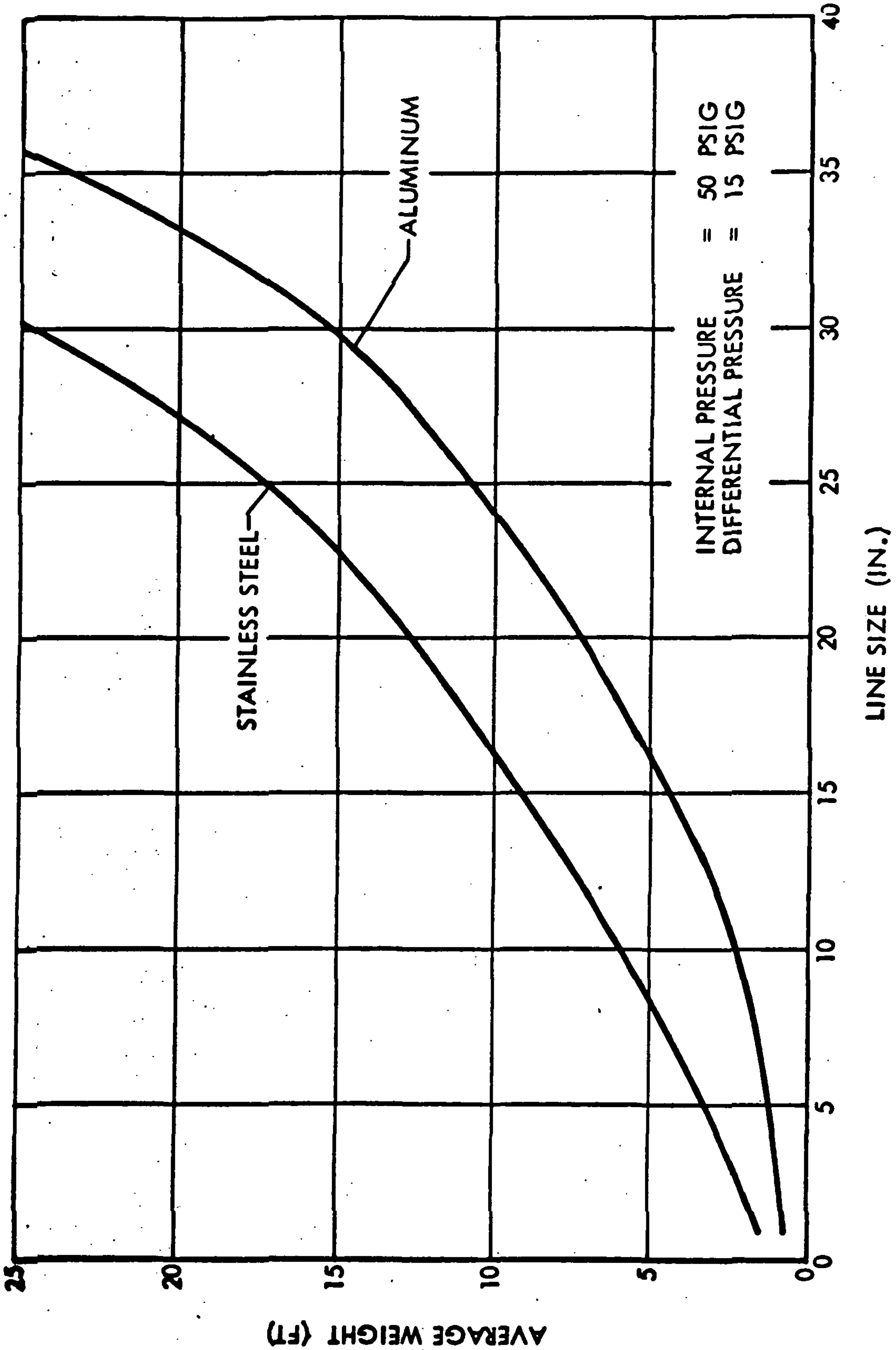

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Fig. 11.1-17 Weight/Foot of Vacuum-Jacketed Line

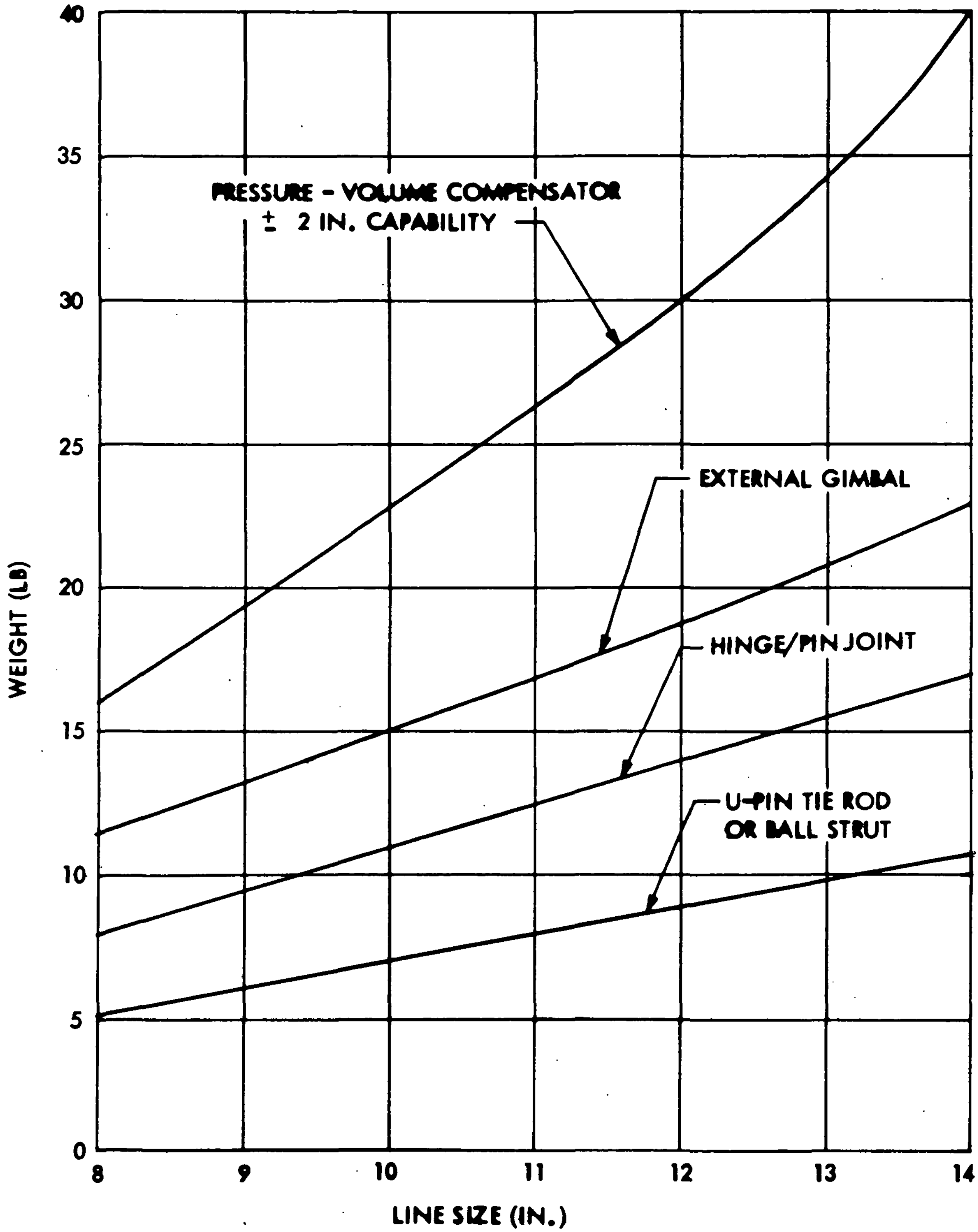


Fig. 11.1-18 Parametric Bellows Data Pressure ~ 40 psi
Ametek/Straza Corporation - Estimated Data

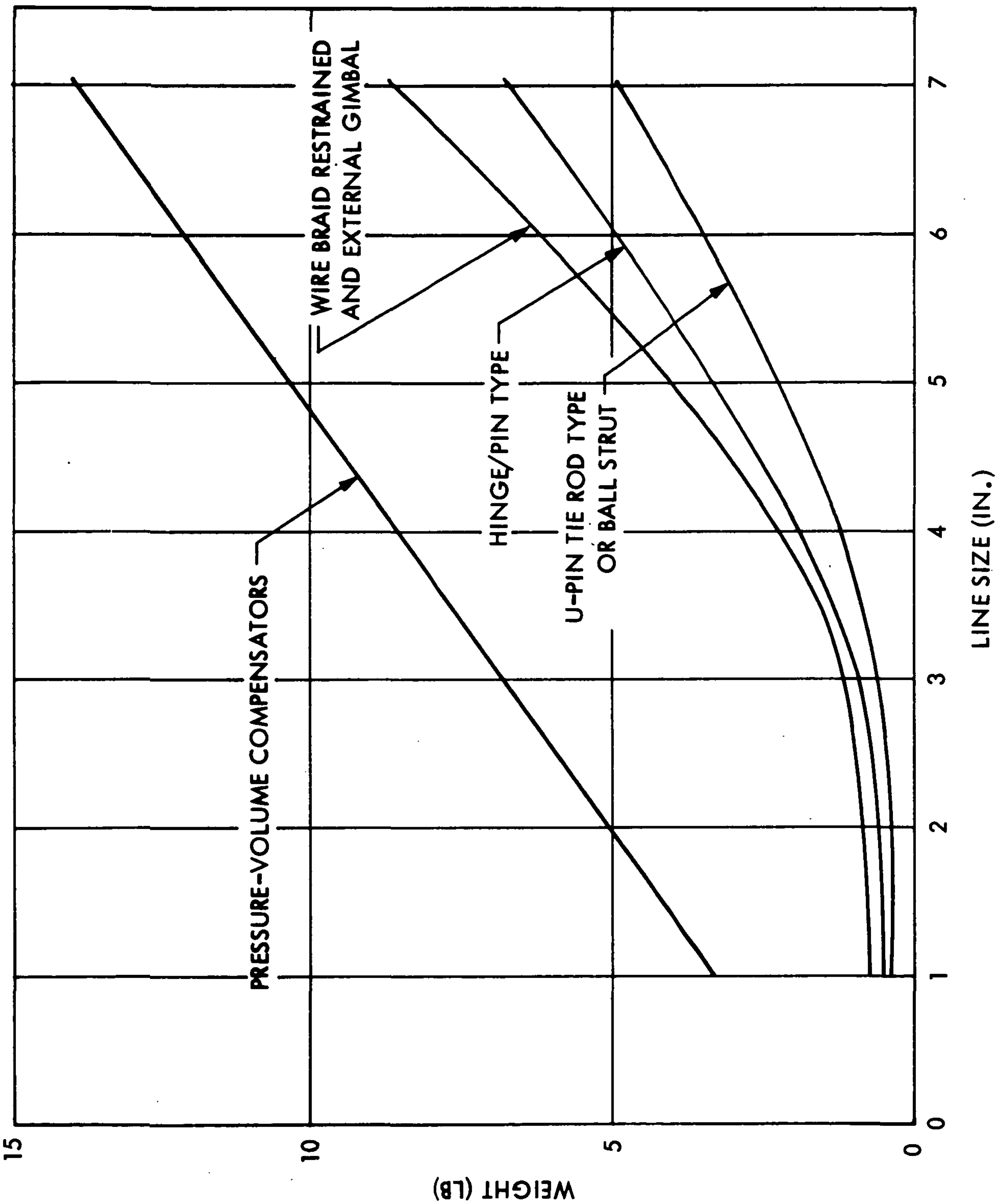


Fig. 11.1-19 Parametric Bellows Data 50 to 150 psi - Arrowhead Bellows Data

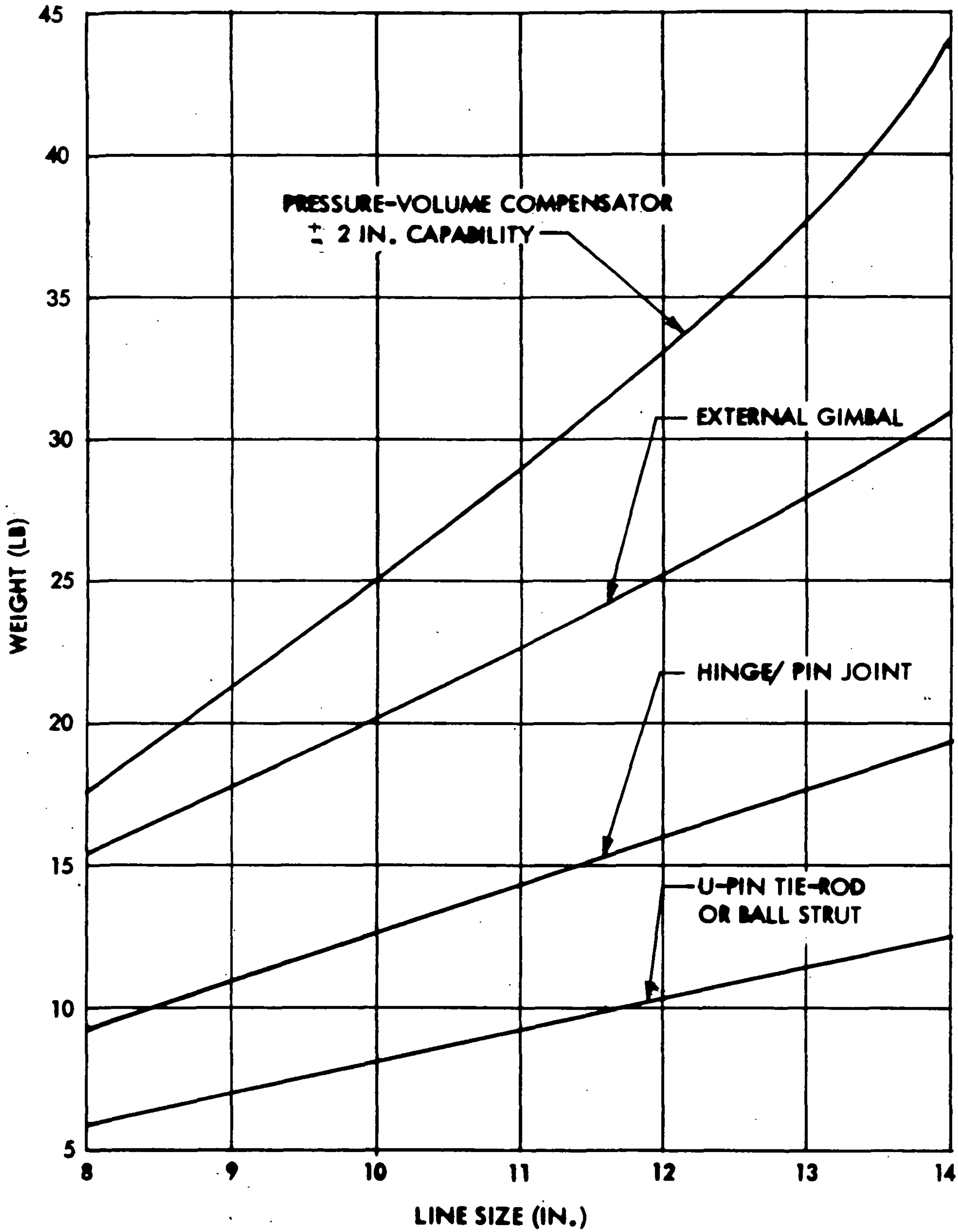


Fig. 11.1-20 Parametric Bellows Data - Pressure ~ 175 psi
Ametek/Straza Corporation - Estimated Data

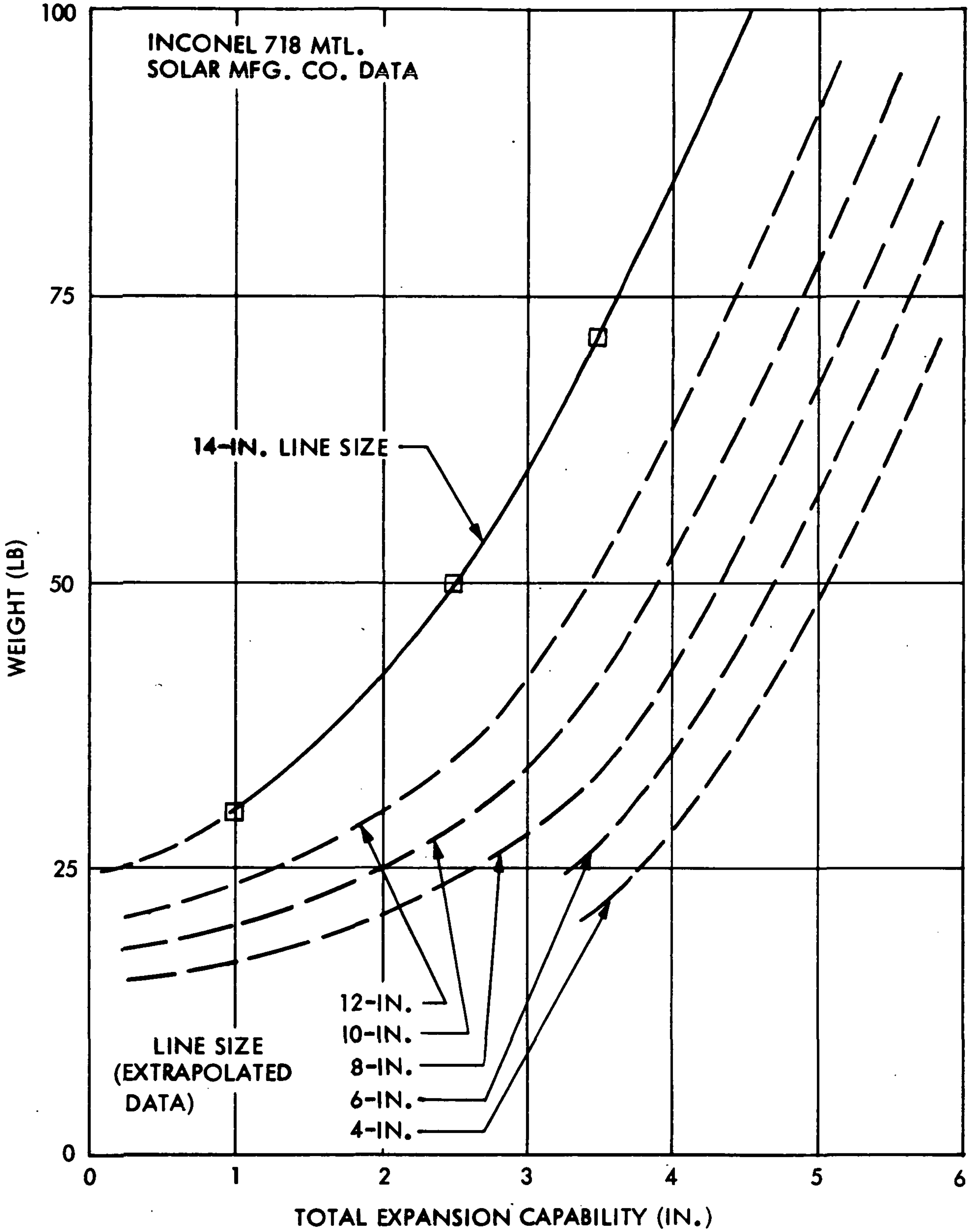


Fig. 11.1-21 Pressure-Volume Compensator (Linear) - Design Curve
LO_2 / LH_2 Service Cycle Life ~ 1000 Missions or 10 Years

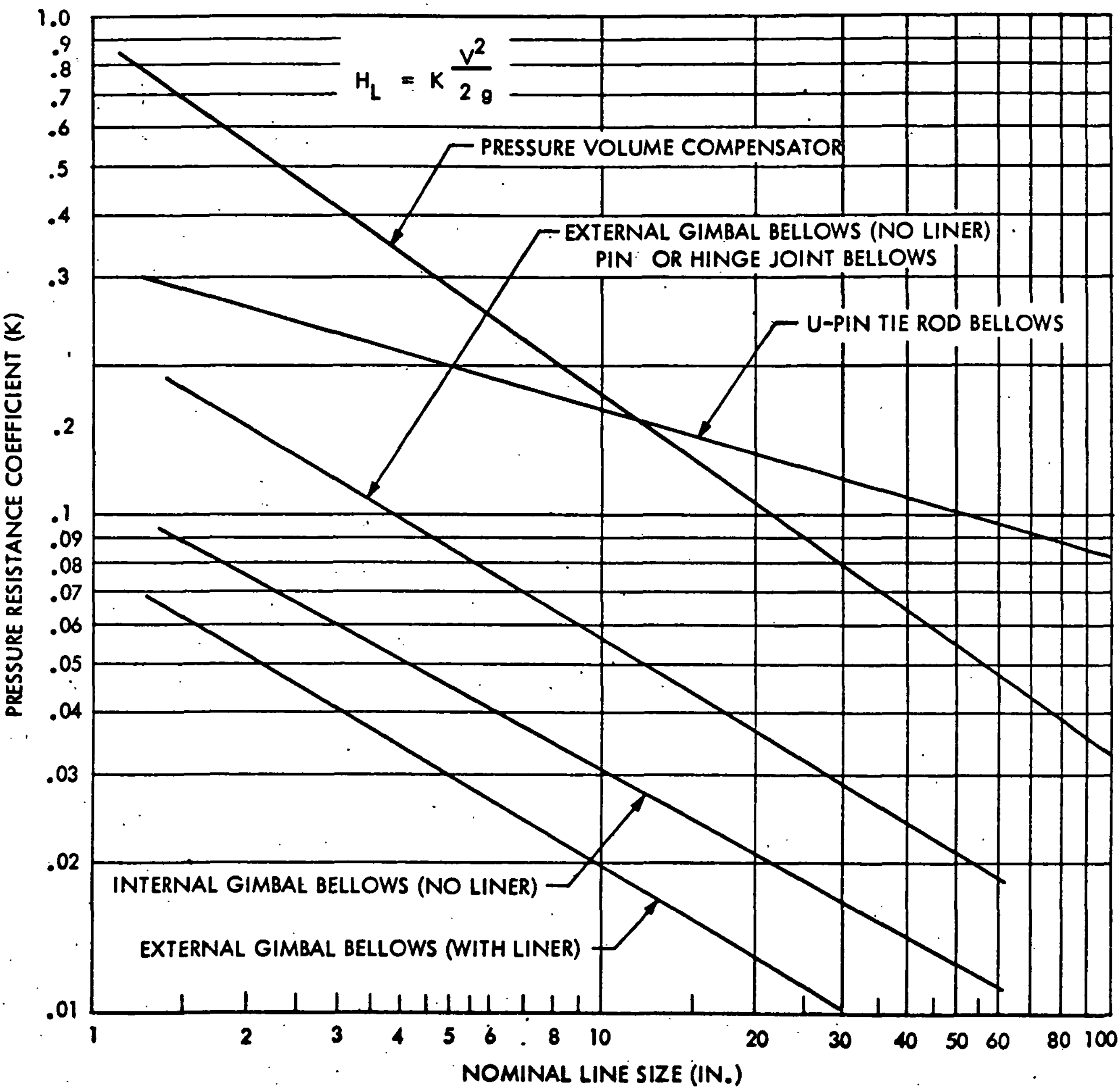


Fig. 11.1-22 Bellows "K" Factor Design Curves

11.1.6 Tank Vacuum Shells

Evaluations were made of tank vacuum-jacketed shells in order to obtain preliminary data for concept analyses. A variety of materials and tank configurations were examined.

Structural sizing of the OMPS shell was based on an ultimate factor-of-safety of 2.0 and a design collapse pressure of 15 psig at room temperature. Vacuum shell geometry and structural arrangement details - such as joints, fittings, insulation, and vacuum-jacket supports - were obtained from a drawing made of a typical tank. Minimum gage constraints were included in the structural sizing. However, joints, fittings, and similar nonoptimum considerations were not included in the "ideal" structural weight.

A summary of candidate structural/material concepts and vacuum shell weights for a spherical LO_2 tank is shown in Table 11.1-4. Comparisons of vacuum shell weights show that the honeycomb sandwich is the minimum weight structural concept. For example, the aluminum honeycomb-sandwich vacuum shell weight is reduced by 77.4 and 75.0 percent relative to monocoque and hat-section-stiffness construction, respectively.

Aluminum, beryllium, and advanced structural composite materials were considered for the honeycomb-sandwich facesheet. Homeycomb-core material was aluminum with 1/4-in. square cells and 0.002-in. foil thickness. The minimum weight "conventional" material, 2219-T87 aluminum, was selected as the leading candidate for honeycomb vacuum shell construction. Also, aluminum was considered best from the following standpoint:

- Forming
- Fabrication
- Reliability
- Cost
- Compatibility with cryogenic fluids
- Resistance to air leakage

Table 11.1-4

SUMMARY - CANDIDATE STRUCTURAL/MATERIAL CONCEPTS AND STRUCTURAL WEIGHTS FOR SPHERICAL VACUUM SHELL, LO_2 TANK FOR OMPS

Structural Concept	Material	Vacuum Shell Weight (lb)(1)
1. Monocoque	a. Aluminum	829
	b. Titanium	1,051
	c. Beryllium	271
	d. Boron Epoxy(2)	607
	e. Graphite Epoxy(2)	543
	f. Boron Aluminum(2)	545
2. Hat Section Stiffened	a. Aluminum	749
3. Honeycomb Sandwich(4)	a. Aluminum	187
	b. Beryllium(3)	80
	c. Boron Epoxy(2)	171
	d. Graphite Epoxy(2)	151
	e. Boron Aluminum(2)	191

Notes:

(1) Joints, fittings, and other nonoptimum considerations not included in the "ideal" structural weight.

(2) Isotropic layup (0 deg $\pm$ 45 deg, 90 deg). Minimum gage, t_{min} = 0.020 in.

(3) Minimum gage, t_{min} = 0.010 in.

(4) Aluminum core, minimum gage, t_{min} = 0.002 in., adhesive weight not included.

Among the advanced structural composites, graphite-epoxy is the minimum-weight honeycomb-facesheet material. Because of the biaxial membrane loads, a four-layer isotropic layup (0 deg ± 45 deg, 90 deg) was considered. Minimum wall thickness was 0.020 in. or 0.005 in. per layer. Because of the isotropic layup, the full unidirectional stiffness of the advanced structural composites could not be employed. Comparison of aluminum and graphite-epoxy honeycomb vacuum shell weights shows, 18.9 percent reduction for the latter.

Beryllium is the minimum-weight honeycomb-facesheet material. Relative to aluminum honeycomb, the beryllium vacuum sheet weight is reduced by 57.3 percent. Minimum gage of 0.010 in. was considered for the beryllium-honeycomb facesheet. Because the beryllium-honeycomb sandwich offers extreme structural efficiency and significant weight savings potential, application of this structural/material concept to vacuum shell design should be considered for future development.

Vacuum shell weights and structural sizing data for OMPS tankage are summarized in Table 11.1-5. Aluminum-honeycomb sandwich was considered for the vacuum shells of Tank Nos. 1 to 4. Vacuum shell weight of Tank No. 4 is based on 0.010-in. minimum facesheet thickness and 0.25-in. core height. Because of minimum gage and core height restraints, an aluminum monocoque shell was considered for the relatively small vacuum shell of Tank No. 5.

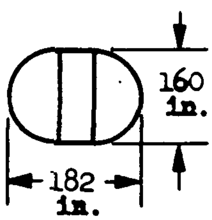
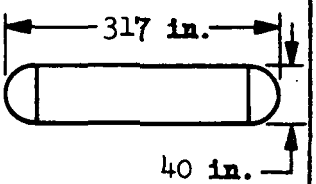
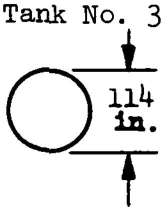
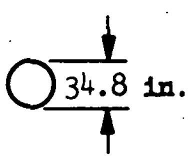
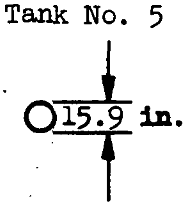
11.1.7 Fluid Acquisition Device Data

The propellant acquisition devices have been discussed in detail in other sections of this report. Information presented here is only supplemental to these discussions.

There are two common wire-cloth weave patterns used to fabricate surface-tension devices: a Dutch twill and square weave. The Dutch twill is formed by a shute wire over two and under two warp wires. The square weave is formed by one strand of wire at right angles to, and over and under, a wire.

Table 11.1-5

SUMMARY - BASELINE VACUUM SHELL WEIGHTS AND STRUCTURAL SIZING DATA FOR OMPS TANKAGE

Tank Configuration	Vacuum Shell Weight	Structural Sizing Data
H_2 Tank No. 1 	Total Weight $\Sigma W = 512$ lb Unit Weight $W - W_{AD} = 0.752 \frac{lb}{ft^2}$ (excluding adhesive)	Aluminum Honeycomb Sandwich $A_z = 681\ ft^2$ surface area $t_f = 0.0170$ in. face thickness $h_c = 1.105$ in. core height $\sigma_f = 36{,}600$ psi face stress
LO_2 Tank No. 2 	$\Sigma W = 215$ lb $W - W_{AD} = 0.663 \frac{lb}{ft^2}$	Aluminum Honeycomb Sandwich $A_z = 324\ ft^2$ $t_f = 0.0113$ in. $h_c = 1.432$ in. $\sigma_{f,\ hoop} = 30{,}400$ psi
LO_2 Tank No. 3 	$\Sigma W = 187$ lb $W - W_{AD} = 0.594 \frac{lb}{ft^2}$	Aluminum Honeycomb Sandwich $A_z = 314\ ft^2$ $t_f = 0.0141$ in. $h_c = 0.796$ in. $\sigma_f = 32{,}000$ psi
LH_2 Tank No. 4 	$\Sigma W = 9.9$ lb $W - W_{AD} = 0.349 \frac{lb}{ft^2}$	Aluminum Honeycomb Sandwich $A_z = 28\ ft^2$ $t_f = 0.010$ in. (minimum) $h_c = 0.25$ in. (minimum) $\sigma_f = 13{,}500$ psi
LO_2 Tank No. 5 	$\Sigma W = 2.8$ lb $W - W_{AD} = 0.396 \frac{lb}{ft^2}$	Aluminum Monocoque Shell $A_z = 7\ ft^2$ $t = 0.27$ in. shell thickness $\sigma_f = 5{,}000$ psi

Although wire cloth can be made from most stainless steels, the most common and readily available cloth is made of 304 stainless. A contending problem concerns imperfections that can exist in large screen panels. In a roll of screen, there may be no imperfections for several feet and then a small area of broken wires may occur; the cloth must be cut to select choice pieces, or adequate repairs must be made.

An important factor in providing a screen that is compatible with propellants is that of cleanliness. A means of eliminating the volatile contaminants is to sinter the cloth about 2,000°F in a controlled furnace. At this temperature, volatile contaminants are boiled off; each wire diffusion bonds to the adjacent wire and the cloth increases its rigidity. Wire reorientation is minimized during working of the cloth.

Aluminum mesh is available in coarser mesh: 50-to-60 microns nominal and approximately 100 microns absolute. Finer meshes are not available because of the inability to draw the fine wire without breaking.

A means of lowering the bubble point of a cloth is to calender (roll) the cloth to reduce the pore size. Aluminum mesh has been successfully calendered to a lower bubble point. The aluminum cloth increases in stiffness as it is calendered. Aluminum cloth materials are 5056 and 6061 aluminum alloy.

Another material used to fabricate surface-tension devices is photo-etched foil stock. Uniform patterns of any pore shape can be generated by the etching process.

It has been found, in comparing photo-etched material that has circular holes with the woven Dutch twill mesh, that the circular-hole material will support a higher hydrodynamic head compared to an irregular shaped hole of the same size. Whereas the metal-cloth mesh will wick, the circular-hole material will not. The Dutch twill mesh will rewet, but perforated material will not because of the absence of capillary passages.

Tests have been conducted with porous plates made of sintered metal powders. Although a very low micron rating can be achieved with porous plates, the pressure drop through the material becomes dominant at the expense of reducing the hydrodynamic head that can be supported during expulsion.

In design of a surface tension system, the hydrodynamic head that can be supported for a given liquid is controlled by the pore size or wire-cloth bubble-point rating. The pressure drop through the pores of a given screen is minimized by a greater flow surface area. This can be accomplished through pleating the fabric in designs that will allow this approach.

If the pores of the screen material are too small, the device will tend to become a filter. This may or may not become a problem, depending upon propellant solids content. Propellants should be filtered to reach a maximum average particle size of 10-to-20 microns, with maximum individual particles up to 40 microns. However, most propellant procurement specifications and inspection procedures are inadequate. The approximate pore diameters of screens are as presented in Table 11.1-6.

Table 11.1-6

SCREEN PORE SIZES

		Equivalent Pore Sizes	
Type Weave	Weave	(in. X10^{-4})	(microns)
Square Mesh	100	55	140
	200	30	77
	400	15	38
Dutch Twill	24 x 110	55	140
	30 x 150	41	105
	30 x 250	28	73
	50 x 250	24	62
	80 x 70	12	31
	165 x 1,400	7	18
	325 x 2,300	2	5

11.1.8 Insulation Subsystems and Related Analyses

The insulation subsystems considered for the cryogenic subsystems evaluated were:

- Insulation for long-time storage. This requires the use of multilayer insulation which is effective only in vacuum.

- Insulation for groundhold and ascent. The insulation employed may be foam, purged batting, or propellant gas (held in honeycomb or some other surface tension device).

11.1.8.1 Multilayer Insulation for Tankage. This insulation was examined through the following steps:

(1) Generation of parametric data

(2) Evaluation of the effect of insulation on subsystem performance

(3) Examination of multilayer insulation properties as affecting the applications

(4) Purging

11.1.8.1.1 Parametric Data Generation. These data were generated on the following multilayer insulation composites:

- Double-aluminized mylar-silk netting (2 layers)
- Double-goldized mylar-silk netting (2 layers)
- NRC-2

Effective thermal conductivities for the installed conditions were selected by examination of existing data. One of the principal references was LMSC Report, "Investigation Regarding Development of a High Performance Insulation System," Contract 8-20758, July 1968. The parametric data are presented in the Task Reports.

11.1.8.1.2 Insulation Effects on Subsystems. The effects of insulation on subsystems was examined to determine the importance of insulation parameters. These data were presented in Section 9.1 for the Orbit Maneuvering Propellant System. These analyses indicated that the type of insulation system had very little effect upon the overall system performance. The types of multilayer insulation composites will optimize (from the standpoint of subsystem weight) at different insulation thicknesses.

11.1.8.1.3 Multilayer Insulation Properties. Multilayer insulation properties were examined for the shuttle application. Current information being generated is being produced in "Effect of Environment on Insulation Materials", NAS3-14342.

The studies have produced several generalized conclusions:

- Protection of multilayer insulation from the atmosphere and from light is essential to the long-life application.
- The insulation composite should be capable of exposure to 350°F for a short period during reentry. Kapton film has the potential for this.
- Goldized mylar and Kapton appears to be more resistant than aluminized films.
- Gold coatings have poorer adhesion than aluminized coatings.

Several conclusions have been indicated by currently available data:

- Aluminized film is probably the most satisfactory material for use in vacuum insulation.
- Goldized film is desirable for applications in which mild environmental exposures or occasional accidental environmental exposures may occur.

- Kapton film is needed for heat protection.

- Vacuum jacketing is the most satisfactory method of protecting multilayer insulation.

11.1.8.1.4 Multilayer Purging System. The multilayer purging system analyses are presented in Section 9.7, Purging, Inerting, and Pneumatic Supply System. As indicated in these analyses, purge gas heating is necessary to maintain purge bag exterior temperatures if foam or other materials are not employed to keep up the exterior temperatures. The choices for the purge system are:

- Liquid-Hydrogen Insulated Tanks

  (1) Helium-purged multilayer with a soft shell (bag)
  (2) Helium-purged multilayer with a hard shell
  (3) Helium-purged multilayer with a hard shell with exterior foam
  (4) Helium-purged multilayer with foam on tank
  (5) Nitrogen-purged multilayer with foam or batting on tank
  (6) Nitrogen-purged multilayer with foam inside tank

- Liquid-Oxygen Insulated Tanks

  (1) Nitrogen-purged multilayer

A. Liquid-Hydrogen Tank Insulation Purging Concepts

The examination of purging of insulation on liquid-hydrogen tanks resulted in several conclusions:

a. The soft-shell (bag) helium-purge insulation has the lightest weight but presents problems in obtaining a satisfactory bag. Materials selected for either a flexible or semirigid purge bag must provide the following functions:

- Gas Barrier (for He, N_2, air and moisture)
- Fabric reinforcement
- Lamination adhesive
- Seam sealing
- Seam reinforcement
- Flanges for sealing to mounting and plumbing connections
- Seals for final installation

Hot-gas flow into the vehicle base makes a high-temperature capability desirable. Most common films are eliminated from consideration by a $350^{\circ}F$ requirement. Of the films that will withstand $350^{\circ}F$, Kapton provides the best strength-to-weight ratio and durability. However, the moisture-vapor transmission rate of Kapton is high.

FEP Teflon offers the oxidation resistance needed for $350^{\circ}F$ and a low water-vapor transmission rate, but free film or film-to-fabric laminates would tend to heat shrink at this temperature. FEP Teflon can be bonded readily by fusion that must be sodium-etched to provide a surface for bonding or sealing with adhesives.

The desirable properties of both materials are combined in a commercially available Kapton coated with FEP Teflon. This provides one surface for heat sealing during fabrication of the subassemblies and a surface that is bondable by adhesives and sealants without special treatment. This material would also offer greater resistance to pinholing due to handling than would uncoated Kapton.

Thickness of Kapton would be decided on the basis of durability vs weight tradeoffs. The minimal thickness of FEP available for the given thickness of Kapton is desirable in order to save weight.

Beta glass cloth is attractive for the reinforcement of the gas barrier film. This material is available in a number of styles. The material selected would represent a balancing of strength, durability, and weight considerations. The glass cloth would be bonded using a polyamide polyamid-polyester laminating adhesive such as developed by the Schjeldahl Company. This adhesive has been used to bond glass cloth to Kapton for a variety of aerospace uses.

If FEP-coated Kapton is used, seams would be sealed primarily by fusion-bonding a tape having a coating of FEP Teflon to the FEP Teflon side of the laminate. Also, seams could be sealed by fusion-bonding FEP Teflon with Kapton strips over surfaces to be sealed and then using an RTV silicone (GE-RTV-156) as the adhesive-sealant. If uncoated Kapton is used, seams would be made by adhesive-bonding only.

Reinforcement of seams would be accomplished by the use of a beta glass backing for the sealing tape. If the strength of this seam proves inadequate, the glass cloth side would be joined using a silicone rubber adhesive and a tape containing glass cloth.

b. Helium-purged multilayer with a hard shell is a heavier system than that of a soft shell. A shell of fiberglass laminate is a logical approach.

c. Helium-purged multilayer with a hard shell having exterior foam is a heavy insulation system. It does provide some protection to the multilayer from reentry heating. This system provides accessibility to the foam.

d. Helium purged multilayer with foam on the tank produces the same result (elimination of helium heating) as having the foam on a hard shell, but does not provide ready access to the foam. It also raises the multilayer temperature during reentry.

e. Nitrogen-purged multilayer with foam on the tank would eliminate helium from the system. However, foam must be sealed to prevent nitrogen cryopumping into the foam. If nitrogen is trapped in the foam, it is slowly released in vacuum to degrade the multilayer.

f. Nitrogen-purged multilayer with foam inside the tank would be an applicable system only if a satisfactory internal foam system were developed for long-lifetime application. (The importance of such a system is lessened with the adoption of droptanks.) Foam on the interior of tanks is viewed by LMSC as a potential contamination problem.

B. Liquid-Oxygen Tank Insulation Purging Concepts

Nitrogen is the logical purging gas for oxygen-tank insulation. The major purpose of the purging is to protect the insulation from moisture, etc. Consideration of foam underlayer or overlayer is not required, since nitrogen heating is not required.

11.1.8.2 Groundhold and Ascent Insulation for Tankage. The groundhold and ascent insulation for tankage has the following objectives:

- Prevention of air condensation on hydrogen tanks
- Reduction of ice formation on tanks and adjacent structure
- Reduction of propellant or reactant temperature rise and subsequent stratification and effects on tank pressure rise
- Reduction of boiloff during groundhold
- Assistance in childown of tankage

The groundhold and ascent insulations were examined through:

- Parametric data generation
- Evaluation of the effects of insulation on subsystem performance
- Examination of properties

11.1.8.2.1 Parametric Data Generation. Parametric data were generated for three types of systems:

(1) Foam insulation
(2) Purged batting (including shells)
(3) Internal gas barrier

These parametric data are presented in the task reports.

11.1.8.2.2 Evaluation of Effects on Subsystem Performance. The computer analyses of foam insulation, presented in Appendix C, indicated that insulation thermal conductivity did not have a significant effect on the overall system weights. Therefore, the trend would be towards obtaining an insulation at minimum weight to prevent air condensation and minimize ice formation.

11.1.8.2.3 Candidate Concepts. The selection of a system would be very dependent upon material physical properties, resistance to environments, maintainability, and initial cost.

The insulations may have to withstand temperatures of 810°R (350°F) during reentry, depending upon the type of shuttle thermal protection system. This can result in degradation of organics and lead to requirements for an external insulation on foams to reduce temperatures. This had lead some investigators to consideration of internal insulation to assist in this protection. However, this does expose the bondline to increased temperatures.

Possible choices for groundhold and ascent insulation are:

(1) Polyurethane foam applied by spraying. This system presents attractive economies; however, the system ranks relatively low in structural strength and heat resistance.

(2) Polyurethane foam with honeycomb reinforcement. This system increases the strength of the polyurethane system but must be bonded to tanks.

(3) Polypropylene oxide foam. This is a high strength foam but must be installed by bonding.

(4) Internal foam. The internal foam system may either be polyurethane or polypropylene oxide reinforced with fiberglass or other reinforcement. The foams must be bonded to the tanks and overcoatings employed.

(5) Internal surface tension and gas trap systems. These systems employ small capillary passages that fill with gas by virtue of heating rates, when liquid hydrogen is in the tanks, and form a gas barrier. (Also, they inhibit convective gas flow when gas is in the tanks.) The systems involve bonding to the tanks.

(6) Purged batting materials. Batting material purged with helium for liquid-hydrogen applications and nitrogen for liquid-oxygen applications have potential applications. An external shell of some type is required, and this imposes the principal disadvantage. In liquid-hydrogen applications, the high-helium conductivity requires insulation thickness that is approximately 3-to-5 times as thick as foam insulation.

11.1.8.2.4 General Comments Regarding Selection. The selection of a groundhold and ascent insulation will be entirely dependent upon technology advancements and cost considerations. If the trend towards droptanks continues, external polyurethane applied by spraying is undoubtedly the best approach. For reusable internal tanks, polyurethanes have a definite limitation if not locally protected against high-temperature exposure. Cracking is considered to be a major problem that can result in cryopumping of air.

The alternatives listed have many similar problems associated with bonding, temperature resistance, maintainability, etc.

11.1.8.3 Feedline Insulation. Insulation of feedlines presents a somewhat more complex matrix than the insulation of tankage. The feedlines fall into several categories:

- Cryogenic Liquid or Cold Gas Feedlines

  (1) Feedlines with cryogenics during groundhold and ascent but not required to be used after reaching orbit

  (2) Feedlines with cryogenics on the ground and during ascent, which must contain cryogenics in orbit and possibly during reentry

  (3) Feedlines with cryogenics only in orbit (not required to contain cryogenics in the atmosphere)

- Heated Gas Feedlines

  (1) Feedlines with gases which are under higher ambient conditions during groundhold and ascent but are not required to provide insulation after reaching orbit

(2) Feedlines that may contain gases at a higher temperature than ambient on the ground, in orbit, and possibly during reentry

(3) Feedlines that contain gases under higher than ambient conditions only in orbit (not required to provide insulation in the atmosphere)

The feedline insulation examinations have involved the feedline and feedline component studies presented in Section 11.1.5 . Evaluations have included:

- Parametric data generation
- Candidate concepts
- Examination as part of subsystems

11.1.8.3.1 Parametric Data Generation. These data were generated for:

- Feedlines insulated with NRC-2 multilayer insulation
- Feedlines insulated with foam

The data are presented in the Task Reports.

11.1.8.3.2 Candidate Concepts. Candidate concepts were formulated considering the feedline insulation categories previously presented. The candidates for liquid-hydrogen feedline insulation are presented in Table 11.1-7, and the liquid oxygen-candidates are presented in Table 11.1-8. Candidates for heated gas feedlines are presented in Table 11.1-9.

Table 11.1-7

CANDIDATE FEEDLINE INSULATIONS - LIQUID-HYDROGEN FEEDLINES

Cryogenics in the Lines During Ground-Hold and Ascent	Cryogenics during Groundhold, Ascent, and Orbit	Cryogenics during Groundhold, Ascent Orbit, and Reentry	Cryogenic only in Orbit
• Vacuum-jacketed lines with multilayer	• Vacuum-jacketed lines with multilayer	• Vacuum-jacketed lines with multilayer	• Multilayer Insulation sealed in Filtered Breathing Bag
• Foam Insulation	• Multilayer purged with helium, vented on ascent-soft bag-Filtered breather	• Multilayer purged with helium, vented on ascent with controlled purging on reentry-soft bag	
• Helium-Purged Fiberglass Batting-Soft bag			
• Helium-purged Fiber-glass Batting-Rigid purging shell	• Multilayer purged with helium, vented on ascent-Rigid purging shell-Filtered breather	• Multilayer purged with helium, vented on ascent with controlled purging on reentry-Rigid purging shell	
	• Rigid purging shell with internal foam with multilayer on line-Purged inner space	• Rigid Purging shell with internal foam with multilayer on line-Purged inner space with reentry purging	
	• Rigid purging shell with internal fiber-glass batting with multilayer on-line purged inner space	• Rigid purging shell with internal fiber-glass batting with multilayer on line-purged inner space with reentry purging	

Table 11.1-8

CANDIDATE FEEDLINE INSULATIONS - LIQUID-OXYGEN FEEDLINES

Cryogenics in the Lines During Ground-Hold and Ascent	Cryogenics during Groundhold, Ascent, and Orbit	Cryogenics during Groundhold, Ascent Orbit, and Reentry	Cryogenic only in Orbit
• None • Foam Insulation • Nitrogen purged fiberglass batting-soft bag • Nitrogen purged fiberglass batting-Rigid purging shell	• Multilayer purged with nitrogen, vented on ascent-soft bag • Multilayer purged with nitrogen, vented on ascent- Rigid purging shell	• Multilayer purged with nitrogen, vented on ascent-soft bag-Filtered breather • Multilayer purged with nitrogen, vented on ascent-Rigid purging shell - Breathing Bag	• Multilayer Insulation sealed in Filtered breathing bag

Table 11.1-9

CANDIDATE FEEDLINE INSULATIONS - HEATED GAS FEEDLINES

Insulation for Groundhold and Ascent (no Orbital Use Required)	Insulation for Groundhold, Ascent, Orbit, and Possibly Reentry	Insulation for Orbital Use Only
• None	• None	• None
• Foam - Type dependent upon temperature	• Multilayer Insulation - Nitrogen Purged only if temperature is less than ambient in atmosphere. Otherwise, sealed in breathing bag.	• Multilayer Insulation - Sealed in breathing bag
• Fiberglass mat - may be nitrogen purged if excessive condensation or icing occurs	• Fiberglass mat - may be nitrogen purged if excessive condensation or icing occurs	

11.1.8.3.3 Examination of Feedline Insulation in Subsystems.

A. Orbit Maneuvering Propellant Supply

Feedline insulation approaches were considered most extensively in the OMPS calculations. In these studies, it was necessary to consider storage of liquid hydrogen and liquid oxygen in feedlines for extended periods. These evaluations indicated that liquid-hydrogen storage in feedlines for extended periods (days) was not practical. Liquid oxygen could be effectively stored only by employing supplemental cooling with hydrogen.

Vacuum-jacketed lines were examined for use with the OMPS subsystem. These lines result in significant weight penalties and should be employed only if it is considered essential to have the OMPS ready for operation at ground launch or to provide the ultimate system for insulation protection. The OMPS feedlines can be drained of liquid hydrogen prior to reentry and only cold-helium purging of insulation is required.

B. Orbit Injection Propellant Supply

In the OIPS evaluations, the relatively high-heat input from the main engines tends to reduce the sensitivity to feedline insulation. It was found that increasing the circulation rates by 50 to 100 percent could offset any heat-reduction advantages of vacuum-jacketed lines or thicker foam-type insulations.

11.1.8.3.4 Selection Considerations. As will be recommended in the technology evaluations, feedline insulation system development is needed. Considering the available information, some of the better candidates can be recommended.

A. Lines Containing Cryogenics During Groundhold, Ascent, and On-Orbit

For this case, multilayer insulation is required. The recommendation for line insulation is the NRC-2-type insulation purged during groundhold and ascent. To eliminate helium heating on hydrogen lines, a fiberglass cover with interior foam is desirable. The covers would be designed to be removable.

B. <u>Lines Containing Cryogenic During Groundhold and Ascent</u>

One of the previously discussed foam insulations is considered to be a satisfactory approach, with adequate circulation. Adhesion of the foam and sealing of bondlines are recognized problems. Purging of certain component areas is considered necessary even with this type of insulation to prevent cryopumping under the insulation system.

11.2 REUSABILITY AND RELIABILITY EVALUATIONS

Reusability and Reliability evaluations were conducted in basically the same task, inasmuch as these two areas are so closely related in subsystems that must be "reusable". Generally, it has been observed in the performance of this contract and a previous contract (Reusable Subsystems Design Analysis, F04(611)-69-C-0041) that the expressions of "reusability" and "reliability" as developed for expendable systems require considerable explanation and qualification when applied to the shuttle. The philosphies and approaches to the shuttle subsystems must tend to adopt aircraft practices that result in a more flexible approach to reusability and reliability.

The term "Reusability" has not been given the connotation of being a quantitative term but has been considered somewhat qualitative. The term "Reliability," on the other hand, has been given too much of a connotation of being quantitative and, as such, has lost much of its impact upon design. It is difficult to substitute a single word for "Reusability," however, it must take on the connotation of a quantitative term (lifetime, cycle life, etc.). A substitute for the word "Reliability," in terms of the shuttle application is possible, by using the word "Predictability." It is possible to combine the concept of Reusability and Reliability into the single concept of "Predictability" for the shuttle application. This combines the data collection functions of Reusability and Reliability, which are so closely related in the shuttle application.

11.2.1 Reusability and Reliability Data Collection

The collection of data regarding reusability and reliability was considered to be very important to the success of the evaluations. AiResearch and Lockheed cooperated in this effort.

Schematics prepared for AiResearch evaluation were discussed in Sections 9.1 through 9.7. The components selected by AiResearch were examined and the following supplied:

- Lifetime estimates (cycles, hours of operation, etc.)
- Most likely malfunction
- Failure rate estimate

Lockheed collected lifetime and failure rate estimates on the balance of the components in these schematics. When the schematics were iterated and expanded, the data for the additional components were collected.

It is believed that the best available and applicable lifetime and failure rate data were utilized in these studies; this information is provided in the Task Reports. Where lifetime data were not available, these were estimated by the technique presented in subsection 11.2.3.

11.2.2 Initial Redundancy Evaluations

Initial functional redundancy evaluations were performed to provide a guide to the safety evaluations and schematic iterations by finding the "weakest" components in the subsystems.

Functional redundancy appraisals have been accomplished using an iterative procedure. The SETA II program was employed in these analyses; this computer program has extensive capability to evaluate the effect of redundancy upon reliability. The SETA II computer program was allowed to insert any number of redundancies necessary to bring a component up to a point for satisfying a reliability effectiveness ratio. From the run data obtained, it was then possible to establish the identity of these components requiring redundancy characterization. Then, either a component required no redundancy, or, it required some particular kind of redundancy. The next step, therefore, was to select the type of redundancy that best fits the component and subsystem function

requirements and then constrain the component to that type of redundancy. A second run of the SETA II program with component constraints was made - this time allowing the program the option of selecting only the number of redundancies within the constrained redundancy type.

The analysis considered only those redundancies necessary to assure functional performance with a probability of successfully functioning of at least 0.99. "Weak link" components of the various systems have been identified. The results of the redundancy analyses are presented in Appendix E.

11.2.3 Predictability Evaluations*

Subsystem analyses were made to obtain a quantitative evaluation of component reusability and effects on subsystem reliability. At the same time, comparisons were made of subsystem and integrated system approaches.

The SETA II computer program used in the analyses is specifically designed for reusable spacecraft systems analyses. This program, which considers the "effective useful life" of components at any specified confidence level, automatically replaces components (1) that are about to exceed their effective useful life, (2) notes the replacement, and (3) continues the analysis through the specified number of mission flights.

The term "predictability" as employed in the study relates to the probability that a subsystem or component will conform to requirements over a given period of time. This term is used to indicate not only "reliability" but also the effects of replacement of components as a result of "wearout."

*Include component replacement requirements, reliability relationships, integrated system comparisons, and operational mode comparisons

There exist two probabilities of failure that are considerations in reusable systems:

- The probability of failure per flight, which is a constant for all flights, if constant failure rates for the components may be assumed. This is essentially a function of the effective redundancies in the subsystems and, of course, the failure rates of the components.

- The probability of failure in "N" number of flights, which does not relate to the probability of failure per flight but is an excellent indicator for the comparison of reusable subsystems.

This latter probability of failure is affected by the removal of components, as they reach their respective lifetimes and are replaced by "new" components.

The failure rate versus operating time curve shown in Fig. 11.2-1 provides the basis for reliability and lifetime considerations. In order for constant failure rates to be used, the flat portion of the curve must be the operating range of the component lifetimes.

Component lifetime data are not available for a number of components, since tests to the wearout conditions (increase in failure rate) have not been performed. Studies have been made (Ref. 11-2) which have shown that effective useful lifetimes for components can be estimated from known failure rates.

If it is assumed that existing failure rate data are reasonably good, an estimate of this minimum wearout-failure-free life can be made for any degree of statistical confidence by utilizing the pure-chance chi-square (X^2) estimator.

$$M_L = \frac{2M}{X^2_{\alpha,2}}$$

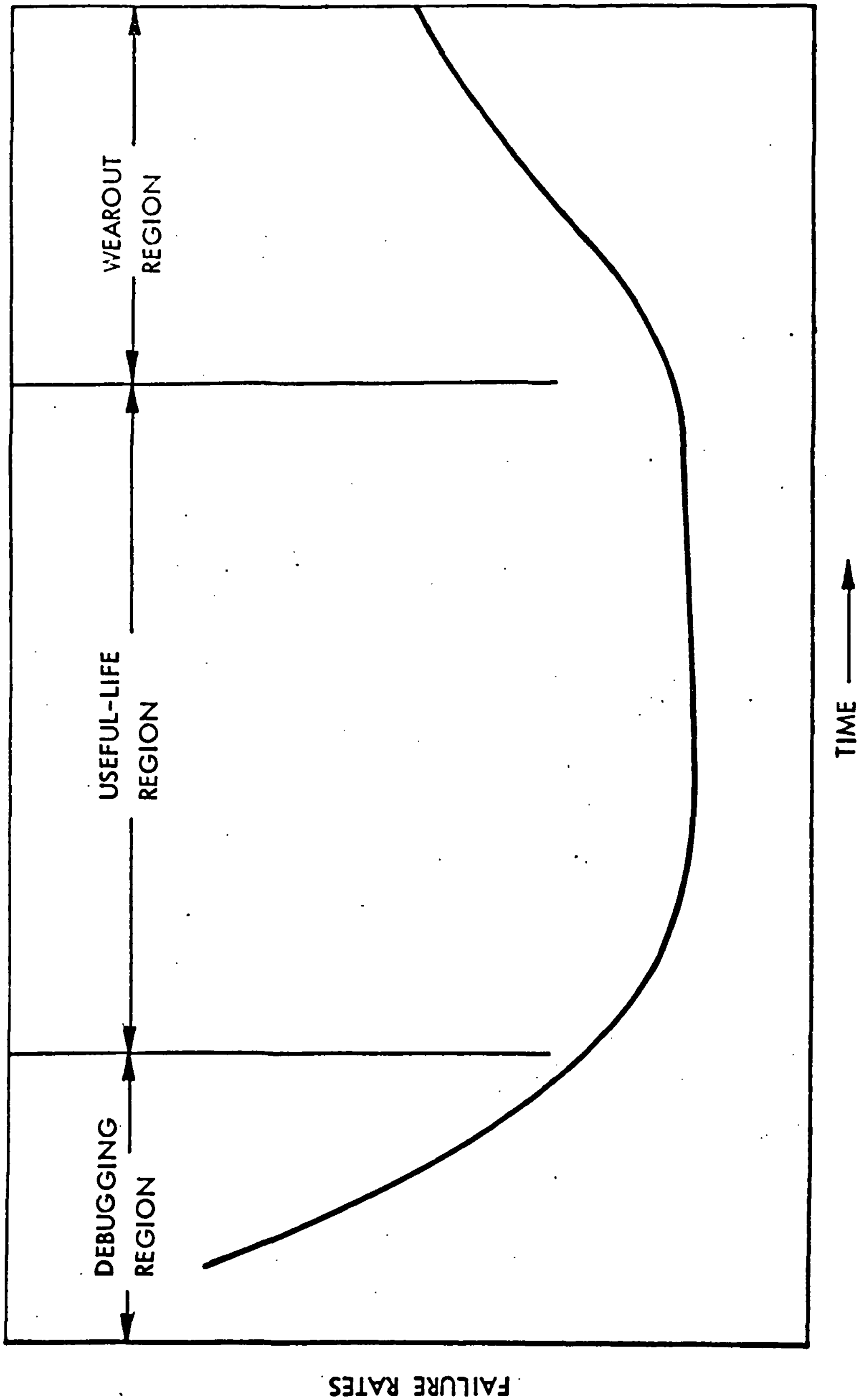


Fig. 11.2-1 Failure Rate vs Time

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where,

M_L = the lower limit of the mean wearout distribution (effective useful lif

M = Mean life to wearout failure (useful life)

X^2 = the pure-chance chi-square number

Subscript α = 1 - desired confidence

Subscript 2 = 2 degrees of freedom associated with zero failures.

The literal interpretation of this estimate (M_L) is: if the mean wearout life is M, as given, one can expect (on the basis of pure chance) that (1 - α) percent of the time the device will not fail due to wearout in less than M hours.

As an example, assure that a pressure switch is claimed to have a mean life of 25,000 cycles. On the basis of pure chance and for a risk (α) of 0.05, the lower limit of the wearout distribution can be expected to be:

$$M_L = \frac{2 \times 25{,}000}{X^2_{0.05,\ 2}} = \frac{50{,}000}{5.99} = 8349 \text{ cycles}$$

That is, there is a 5-percent risk that failures other than those due to wearout will occur over the period of 0 to 8349 cycles. The wearout distribution can not be defined to exist over the range

$$8349 < 25{,}000 \quad M_{max}.$$

This implies that the standard distribution might be

$$\alpha = \frac{25{,}000 - 8349}{3} = \frac{16{,}651}{3} = 5550 \text{ cycles.}$$

The total range might then be construed to be

$$8349 < 25{,}000 < 41{,}651 \text{ cycles.}$$

From the preceding, the following inferences can be made:

- The exponential or pure-chance probability will only hold for mission requirements of less than 8350 cycles.

- The probability that the device will operate continuously for longer than 41,000 cycles is practically zero.

The validity of the estimated standard deviation, which was obtained by using the chi-square estimator, is established by the following considerations. It is well known that all possible families of distribution are, for all practical purposes, between the exponential and the normal. This is shown by the gamma, beta, chi-square, and Weibull families of distribution. In estimation of standard directions, therefore, the minimum value is given by the exponential, since σ^2 = mean, then $\sigma = \sqrt{M}$. The maximum σ for the normal distribution of failures occurs when the range is from t = 0 (or cycles = 0) to the mean, i.e., $\sigma = \frac{M}{3}$. From the example above, $\sigma e = \sqrt{25{,}000} \approx 158$ and the maximum $\sigma_n = \frac{25{,}000}{3} \approx 8333$. Since the estimate of 5550 is reasonably close to the maximum normal, it may be considered a reasonable estimate.

The steps in the analyses of the subsystems and integrated systems were as follows:

- Employment of schematics that satisfy redundancy and safety requirements
- Determination of single mission probability of failure (reliability)
- Determination of the probability of failure in a given number of flights, N, considering replacements.

11.2.3.1 <u>Selected Subsystems and Integrated Systems for Evaluation</u>. Two integrated systems approaches and variations of these approaches were selected; also, individual subsystems were examined as a basis for comparison. The selected systems consisted of:

- System III, as presented in Section 10, consisting of:

  (1) Integrated OMPS/ACPS with pump-at-tank
  (2) Subcritical APU
  (3) Integrated fuel cell/Life support

- System I, as presented in Section 10, consisting of:

  (1) All systems integrated in OMPS tank with pump-at-engine
  (2) Basic construction of subsystem similar to System III

- System I, as presented in Section 10, consisting of:

  (1) All systems integrated in OMPS tank with pump-at-engine
  (2) More optimum construction of subsystems

- Individual subsystems

  (1) OMPS with pump-at-engine
  (2) Subcritical ACPS
  (3) Subcritical APU
  (4) Supercritical fuel cell
  (5) Supercritical life support

11.2.3.2 Duty Cycles and Operational Modes. The selected duty cycles for the systems are very extensive and are presented in the Task Reports.

Two operational modes were selected for operation of the Integrated OMPS/ACPS systems.

Two pump operation schedules were examined as follows:

- Preselected Pump Arrangement (PPA) - This schedule designates a first pump subsystem as prime for the mission, supported by a second pump running on-line with a lighter load. The third pump is a standby.

- Sequential Pump Arrangement (SPA) - This schedule divides load among all pumps for equal operating times, such that when the pumps are operated in a sequenced mode they all receive equal wear and are, in turn, sequenced through primary, secondary, and backup ordering.

The operating schedules for System III are presented in Tables 11.2-1 through 11.2-4.

The integrated OMPS/ACPS with pump-at-tank assumes five OMPS engine burns, with component duty cycles as presented in the Task Reports.

The integrated OMPS/ACPS with pump-at-engine requires different duty cycles for the pump operational modes. One main engine was assumed to operate five times for a total of 800-sec burn time for the preselected pump arrangement model. For the sequential pump arrangement models, all three of the main engines were assumed to operate an average of two times each for an average total burn time of 267 sec on each engine.

11.2.3.3 Comparison of Operational Modes. The preselected pump and the sequential pump operational modes were compared by employing System III. Pump-at-the-tank results are presented in Fig. 11.2-2, and the pump-at-the-engine results are presented in Fig. 11.2-3. As may be seen in these figures, the preselected pump mode of operation results in lower probability of unscheduled maintenance but results in higher component replacements.

It is expected that this indicates a trend which will be found in all "reusable" systems. If one "leg" of the system is selected for operation, the second "leg" operated only in critical periods, and the third "leg" as standby, the reliability will be higher and probability of failure over a given number of missions will be lower than by spreading the operations over all of the "legs". The number

Table 11.2-1

PRESELECTED PUMP ARRANGEMENT SCHEDULE (PUMP-AT-TANK)

Subsystem	OMPS Operation		ACPS Operation		Total Operation	
	Time	Cycles	Time	Cycles	Time	Cycles
Oxygen Supply						
Pump 1	775 sec	5	277 sec	70	1,052	75
Pump 2	775 sec	5	166 sec	20	941	25
Pump 3	STANDBY ONLY					
Hydrogen Supply						
Pump 1	775 sec	5	525 sec	95	13,000	100
Pump 2	775 sec	5	315 sec	20	1,090	25
Pump 3	STANDBY ONLY					
Pump 4	STANDBY ONLY					

Table 11.2-2

SEQUENTIAL PUMP ARRANGEMENT SCHEDULE (PUMP-AT-TANK)

Subsystem	OMPS Operation		ACPS Operation		Total Operation	
	Time	Cycles	Time	Cycles	Time	Cycles
Oxygen Supply						
Pump 1	516 sec	5	149 sec	20	665 sec	25
Pump 2	516 sec	5	149 sec	20	665 sec	25
Pump 3	516 sec	5	149 sec	20	665 sec	25
Hydrogen Supply						
Pump 1	516 sec	5	107 sec	20	623 sec	25
Pump 2	516 sec	5	107 sec	20	623 sec	25
Pump 3	516 sec	5	107 sec	20	623 sec	25
Pump 4	-	-	524 sec	25	524 sec	25

Table 11.2-3

PRESELECTED PUMP ARRANGEMENT SCHEDULE (PUMP-AT-ENGINE)

Subsystem	ACPS Operation	
	Time (sec)	Cycles
<u>Oxygen Supply</u>		
Pump 1	696	65
Pump 2	418	15
Pump 3	STANDBY ONLY	
<u>Hydrogen Supply</u>		
Pump 1	731	90
Pump 2	439	15
Pump 3	STANDBY ONLY	

Table 11.2-4

SEQUENTIAL PUMP ARRANGEMENT SCHEDULE (PUMP-AT-ENGINE)

Subsystem	ACPS Operation	
	Time (sec)	Cycles
<u>Oxygen Supply</u>		
Pump 1	372	22
Pump 2	372	22
Pump 3	372	22
<u>Hydrogen Supply</u>		
Pump 1	390	30
Pump 2	390	30
Pump 3	390	30

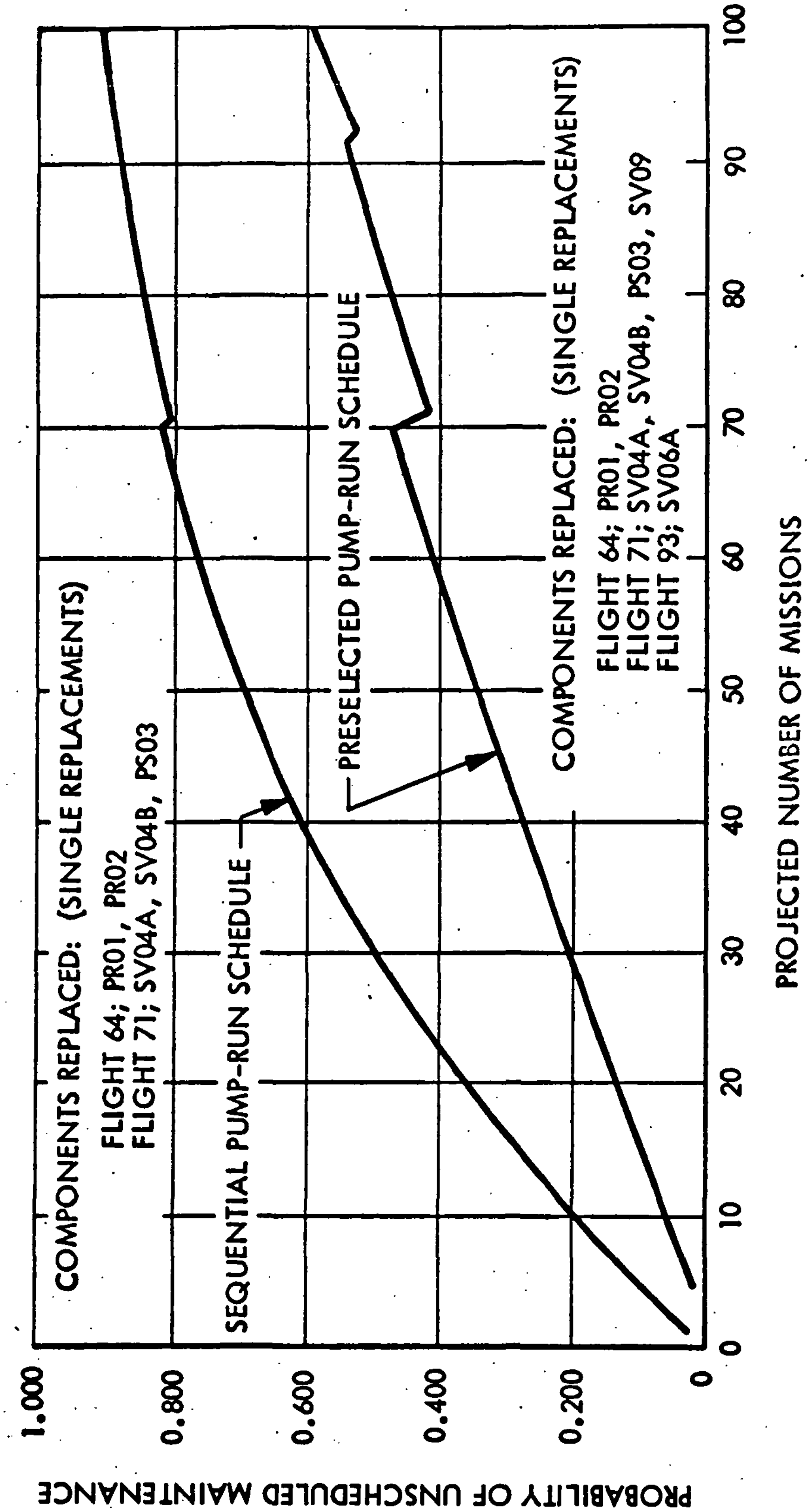

Fig. 11.2-2 System III Pump-At-Tank - Preselected vs Sequential Pump Operation

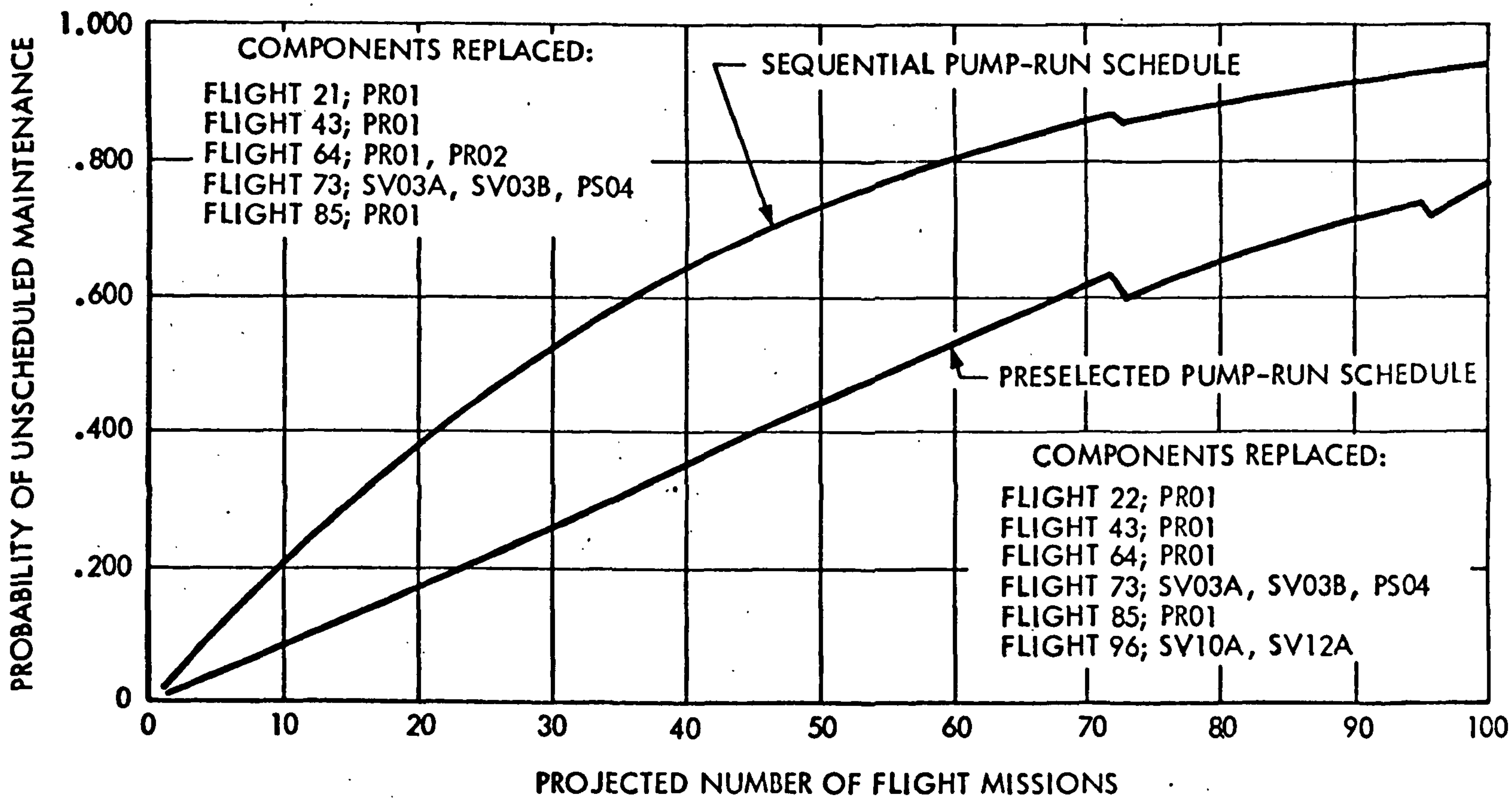

Fig. 11.2-3 System III Pump-at-Engine - Preselected vs Sequential Pump Operation

of component replacements in the preselected "leg" will be higher. Tradeoffs therefore, exist between component replacement and probability of failure over a number of missions.

11.2.3.4 Comparison of Subsystems and Systems. SETA II analyses were used to produce comparisons of system concepts , system variations, and subsystems. The probability of unscheduled maintenance in a given number of missions and the number of replacements are a good indication of the relative suitability of the subsystems for reusable applications.

11.2.3.4.1 Comparison of Pump-at-Engine and Pump-at-Tank. System III was used as a basis for comparing the pump-at-tank and pump-at-engine for both the preselected and the sequential pump operational modes. The comparisons are presented in Figs. 11.2-4 and 11.2-5.

Results indicate that the pump-at-tank has a lower probability of a failure over a given number of missions than the pump-at-engine. This results primarily from the number of components that must be added for the chilldown functions associated with the pump-at-engine.

11.2.3.4.2 Comparisons of Subsystems in System III. The relative predictability of subsystems with a given system are of interest. Results of the Integrated OMPS/ACPS are presented in Figs. 11.2-2 and 11.2-3. The subcritical APU system, shown in Fig. 11.2-6, reflects the lesser duty cycle and less complexity of this subsystem. The EC/LSS system, presented in Fig. 11.2-7, has a severe duty cycle; this results in a number of component replacements. As shown, the component replacements tend to continually adjust the probability of failure to lower values because of the percentage of new components added.

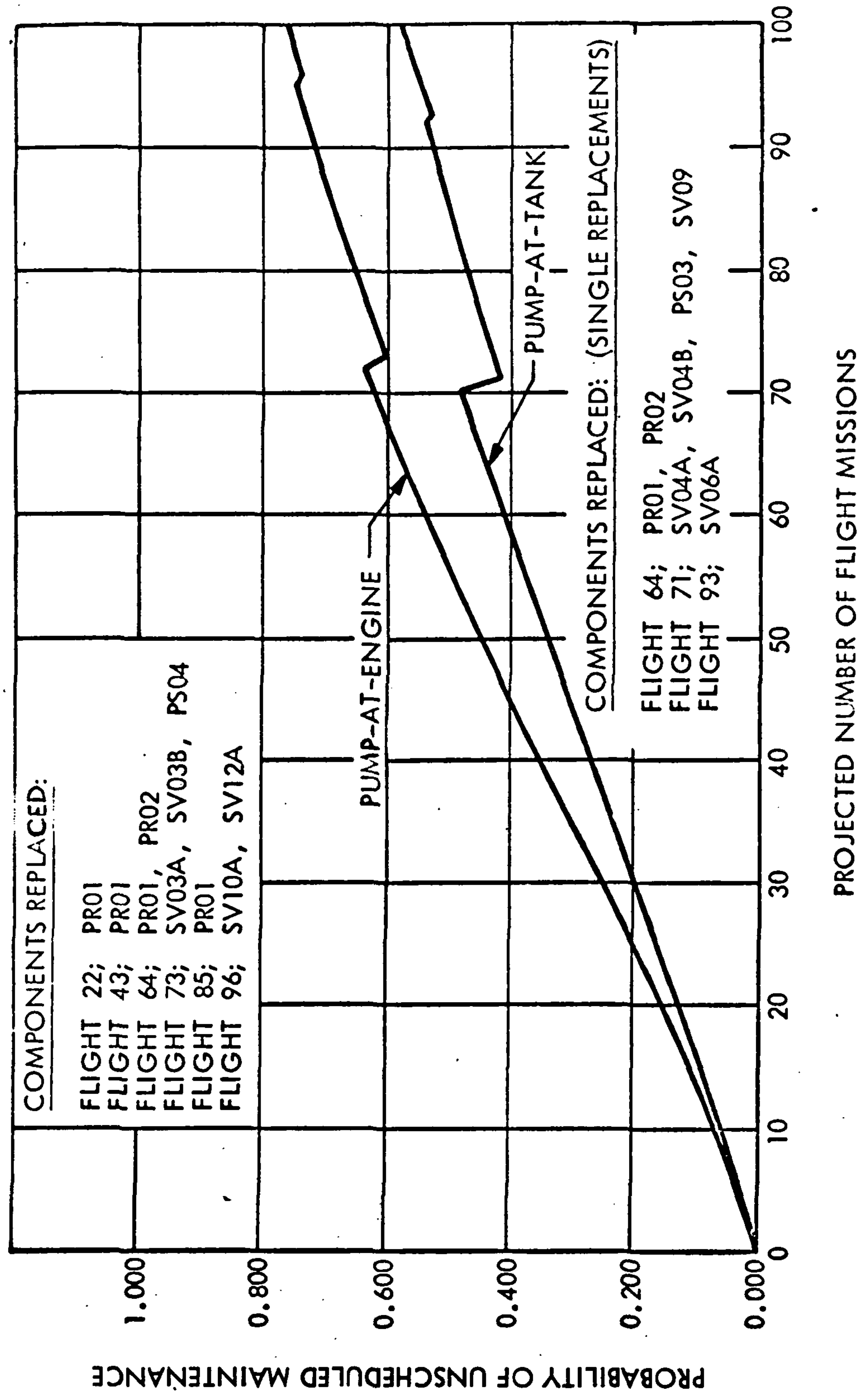

Fig. 11.2-4 Comparison of Pump-at-Tank and Pump-at-Engine - Preselected Pump-Run Schedule - System III

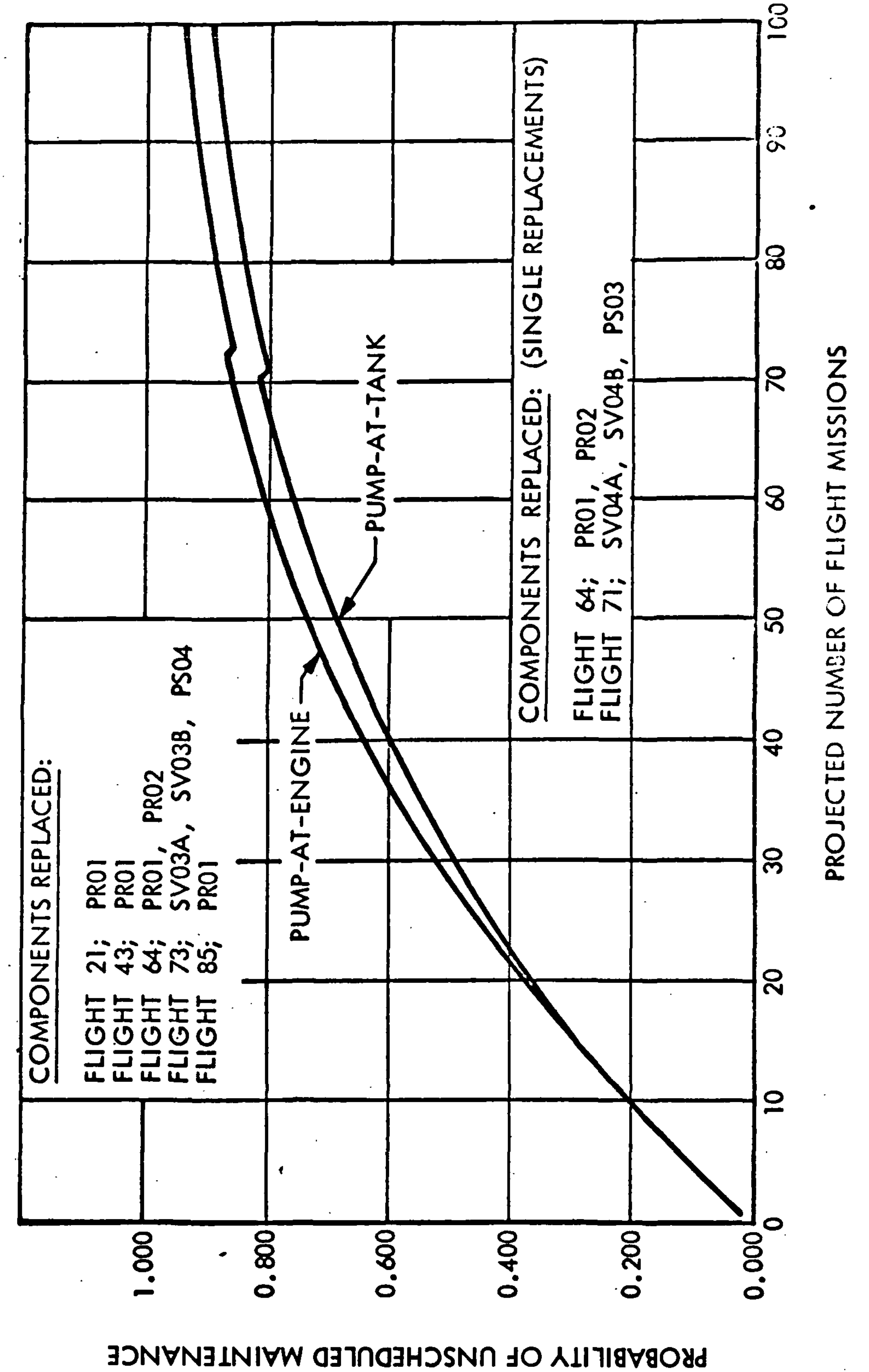

Fig. 11.2-5 Comparison of Pump-at-Tank and Pump-at-Engine - Sequential Pump-Run Schedule - System III

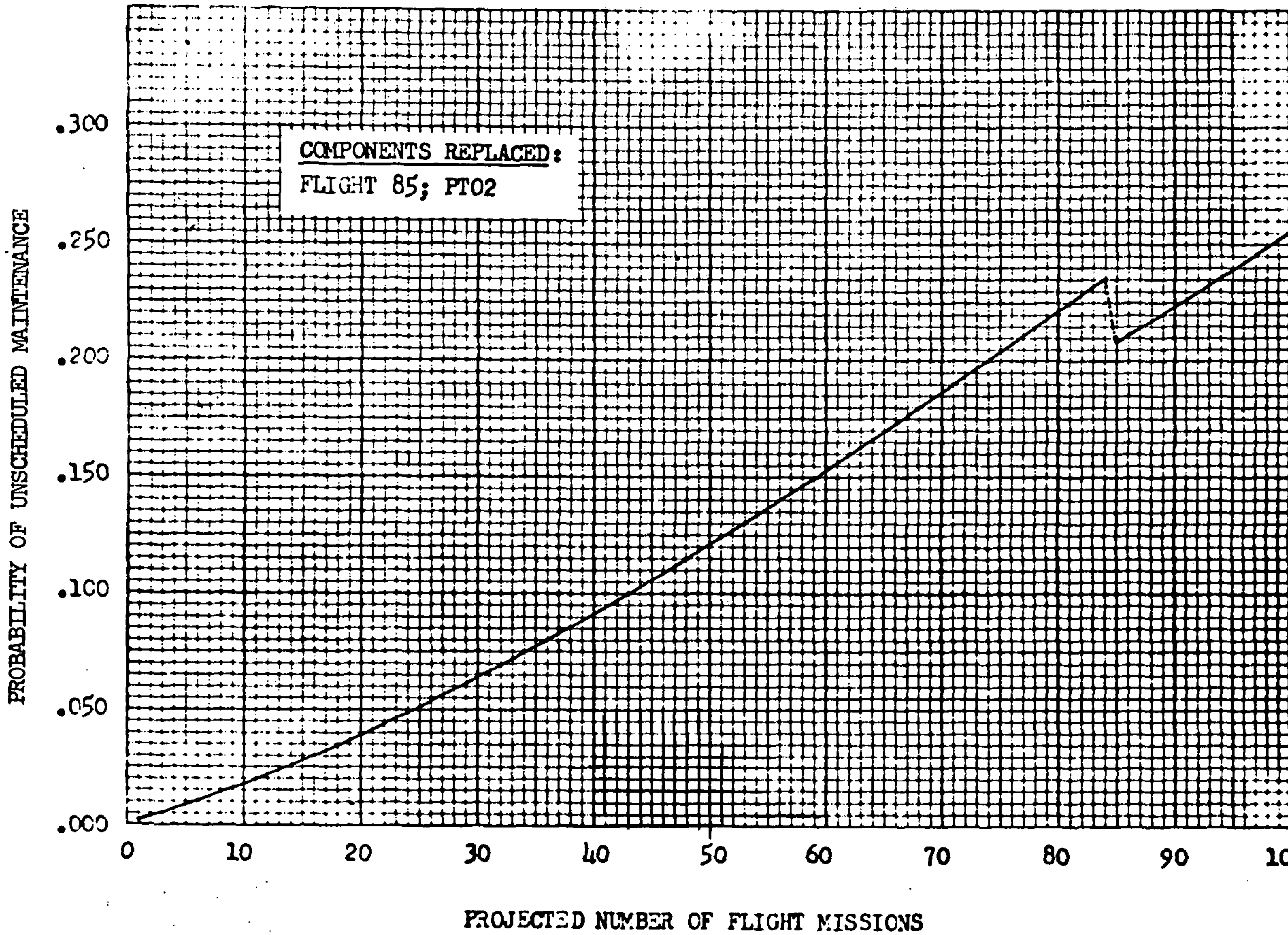

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Fig. 11.2-6 Integrated Auxiliary Power Unit System

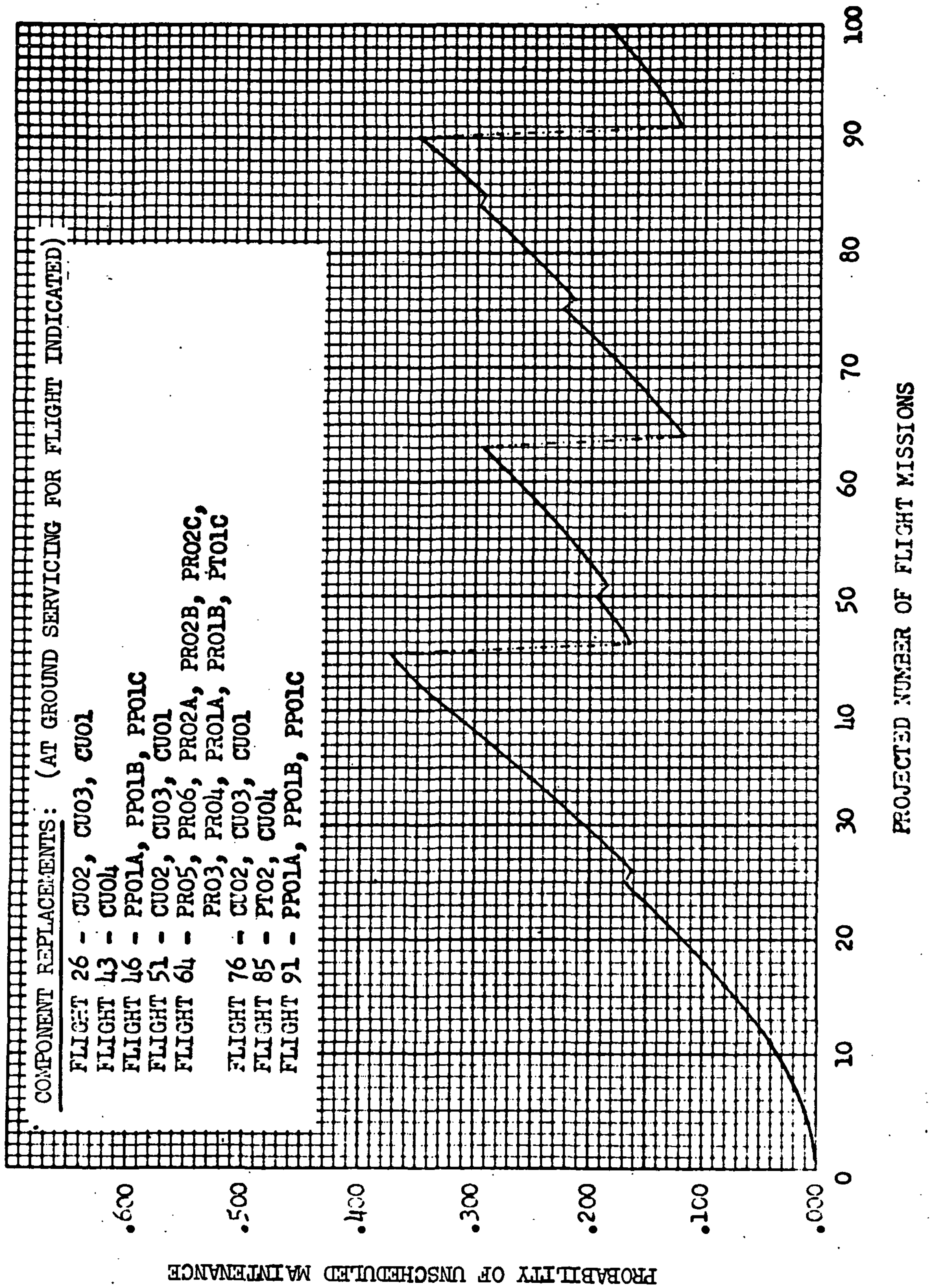

Fig. 11.2-7 Integrated Fuel Cell and Environmental Control - Life Support Systems

D04482

11.2.3.4.3 Comparison of System III and System I. The relative probabilities-of-failure of System III and System I have been compared for the pump-at-engine configurations for the preselected pump mode of operation. Results of this comparison are presented in Fig. 11.2-8. The comparison indicates very little difference in relative probability of unscheduled maintenance over a given number of missions. This is primarily because the components eliminated by going from System III to System I are principally low duty-cycle components.

There is a difference in the probability-of-failure per mission:

Preselected Pump-at-Engine

	Probability of Unscheduled Maintenance	Reliability
• System I	0.006162	0.993838
• System III	0.008416	0.991585

11.2.3.4.4 Comparison of Integrated Systems and Individual Subsystems. Integrated systems and individual subsystems were compared with regard to relative probability-of-failure over a given number of missions, as noted in Fig. 11.2-9. Nonintegrated systems have a slightly higher relative probability of failure. The component replacements are comparable.

The integration of systems does not significantly affect component replacements, as can be seen from these data.

The per-flight probabilities-of-failure differ substantially:

Preselected Pump-at-Engine

	Probability of Unscheduled Maintenance	Reliability
• System I	0.006162	0.993838
• System III	0.008416	0.991585
• Individual Subsystems	0.008972	0.991028

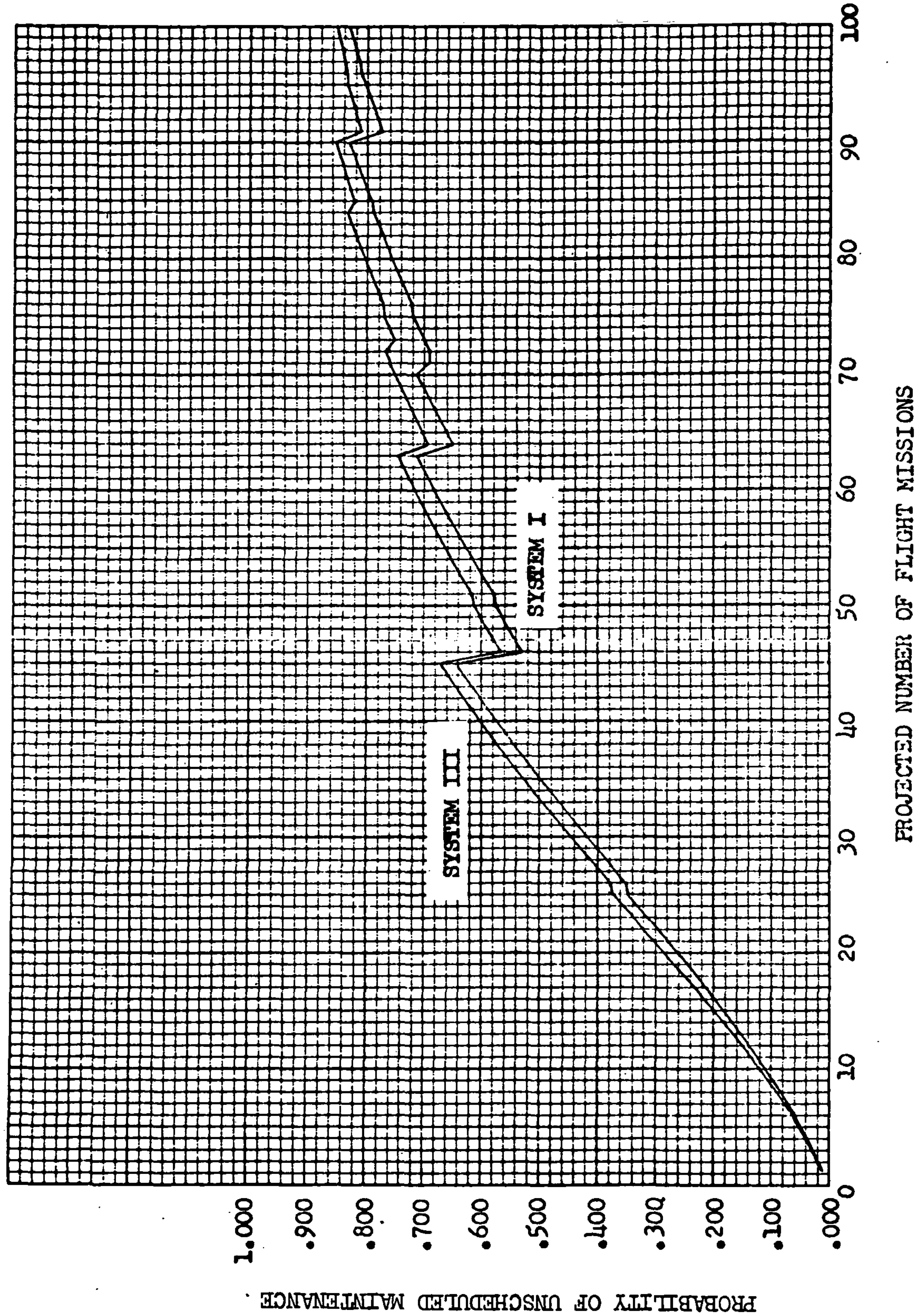

Fig. 11.2-8 Comparison of Systems III and I

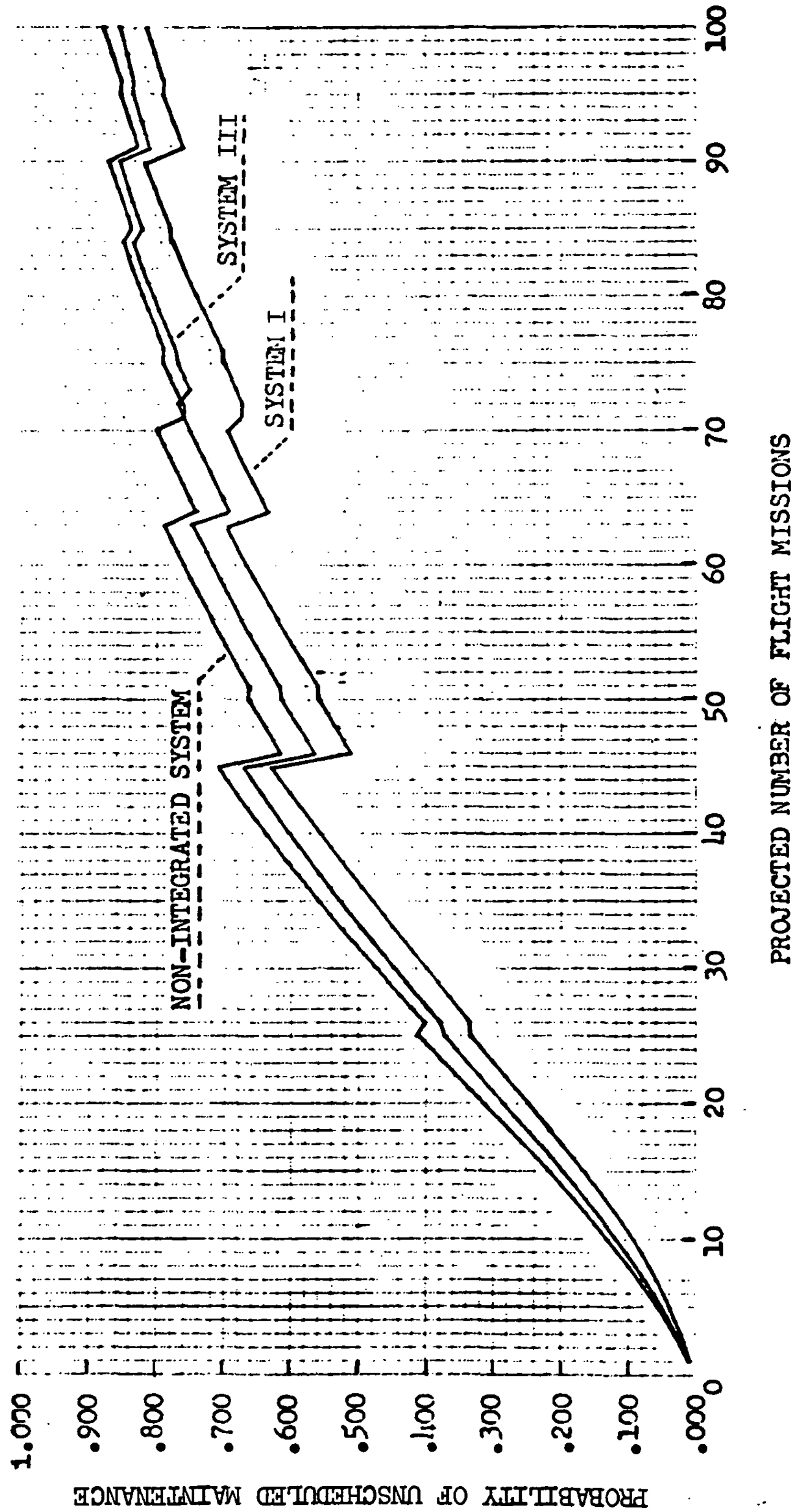

Fig. 11.2-9 Integrated and Nonintegrated Vehicle Cryogenic Systems Analysis (Comparative Data)

11.2.4 Component Reusability Discussions

As previously discussed, the similarity between the shuttle and aircraft requires adoption of an approach to "Reusability" that is similar to aircraft practices. In subsection 11.2.3, the concept of components replacement (while they have a constant failure rate) was discussed. This concept is considered more acceptable for mechanical components than the "inspect and replace" approach, which may be applied to certain components. Applicable components for this approach include insulation, wiring, support structure, and similar inspectable components.

11.2.4.1 Effect of Duty Cycles and Mission Lifetime. One conclusion resulting from the analyses presented in subsection 11.2.3 and from previous studies (such as "Reusable Subsystems Design Analysis," F04(611)-69-C-0041) is that the shuttle duty cycle is not severe from the standpoint of hours of operation, number of cycles, etc. Only the Fuel Cell and the Life Support subsystems require continuous operation during the mission.

The limiting factor for many components will be the length of environmental exposure. Degradation of organic materials - such as thermal insulation, electrical insulation, and plastics - will be governing factors in component replacement.

11.2.4.2 Mechanical and Electrical Component Reusability. AiResearch and Lockheed examined the mechanical and electrical components selected for the subsystems to determine the likely malfunctions. These possible malfunctions should be considered as points that could affect the "effective useful life" or, in other words, result in an increase in failure rate after a certain period of time.

The results of the component examinations are presented in the Task Reports. From examination of these data and making general conclusions, the following brief summary results.

- <u>Valves</u>

  Valve seat leakage is generally identified as a principal failure mode. Organic materials gradually age and are subject to compression set. Metal seats are affected by contamination and stress.

  Actuator failure (principally to open a normally closed valve) is identified as a major shutoff valve failure mode.

- <u>Regulators</u>

  Bellows and diaphragm leakages are the major failure modes. This is expected because of the large number of cycles used by these components.

- <u>Relief Valves</u>

  Bellows leakage is the principal cause of malfunction. Relief valves generally have high failure rates.

- <u>Pressure Switches</u>

  Pressure switches normally fail by shorting which produces a continuous signal. The lifetime of pressure switches in cryogenics is relatively short in comparison to most other components.

11.2.4.3 Tankage Reusability.

11.2.4.3.1 Design Allowables. The factors related to the reusability of tankage for the shuttle have been extensively investigated. A summary of the state-of-the-art is presented in "Reusable Subsystem Design Analysis Study, AFRPL TR-69-210." The entire subject will not be presented in this report.

Design allowables, also represented by safety factors, are employed to account for any differences between (1) actual and calculated stresses and (2) actual stresses and known strength values. The standard design approaches, utilizing ultimate strength and yield strength, assume that the fracture strength is greater than the yield strength and equal to or greater than the ultimate strength; these rely on proper design procedures that incorporate past experience and safety factors to keep the working loads below the yield and ultimate loads and, hence, below the fracture load.

Failure histories illustrated a major shortcoming in conventional design criteria. They did not provide for the possibility that unstable fractures can occur at stress levels that are well below the design limit (yield stress) of a structural member.

"Brittle" failures, indicating no significant gross plastic deformation prior to failure, occur. Analyses of many of these "brittle" failures disclosed a surface or embedded flaw (crack) as the origin of the catastrophic fractures. To assist in providing a solution to this and related problems, a special ASTM committee was formed. With Griffith-Irwin fracture mechanics as a basis, methods of fracture-toughness testing have been proposed by the ASTM committee. For certain applications, these tests have provided an analytical technique, which establishes a quantitative measure of a material's crack tolerance. This has been an important step in the development of a rational procedure for designing against catastrophic failures.

Unstable fracture will occur, according to fracture mechanics theory, when the stress-intensity factor K at the tip of a crack reaches a critical value K_c.

If plane strain conditions prevail, the critical value is K_{Ic}. In turn, the critical stress-intensity factor is a function of the gross stress σ and the critical flaw size $(a/Q)_{cr}$. The parameter Q is determined by the flaw shape, gross stress σ, and material tensile yield strength F_{TY}.

In thick-walled pressure vessels, flaws are often surface or embedded cracks. Slow, stable crack growth to a critical value can occur as a result of exposure to either fatigue-type loading or to certain chemical environments.

Experimentally, it has been determined that for a given chemical environment, there exists for each material tested, a stress-intensity factor $K_{Threshold}$ below which no crack growth and, hence, no failure occurs. Therefore, an initial stress-intensity factor K_{Ii} can be established, such that no crack growth will occur. Threshold stress-intensity factors $\left(K_{Threshold}\right)$ are usually presented in terms of the ratio K_{Ii}/K_{Ic}, for which no stable crack growth occurs. Threshold stress-intensity factors vary widely for different material-environment conditions.

For fatigue loading, no analogous $K_{Threshold}$ has been experimentally established. Apparently, some finite crack growth occurs even at very low values of ΔK (the excursion in stress intensity), arising from the varying stress encountered in fatigue-type loading.

Fracture toughness data are very limited for the alloys being considered for the shuttle cryogenic supply systems. Current safety factors are accepted with general agreement between shuttle contractors. However, it is recognized that some conservatism is likely present in these design allowables.

11.2.4.3.2 <u>Tankage Components</u>. The tankage components might be considered to include:

- Access doors and seals
- Electrical feedthroughs
- Tank heat exchangers

Access doors (manhole covers) present potential leakage regions. Current serrated seals have proven to be effective, but these may become problems in systems requiring repeated reuse. Leakage from seals must be isolated from multilayer insulation by vented covers. Purging must be provided for hydrogen leakage into the atmosphere.

Electrical feedthroughs have been examined for high cycle life. However, failures are likely to occur. Reliability and lifetime data for these components are very doubtful, since "failures" by low leakage may go undetected on current expendable vehicles.

11.2.4.4 Feedline Reusability. The feedline design data presented are based upon a minimum of 10,000 cycles. Designing for high cycle life is basically a function of design allowables and length of expansion joints. The designers have flexibility in tradeoff of weight and cycle life.

Problems associated with vacuum sealoff valves have been previously discussed. The effectiveness and lifetime of these valves should be improved.

11.2.4.5 Insulation Reusability. Insulations are organic materials, which are subject to gradual degradation if exposed to light, air, and moisture. Protection from the environments, such as in a vacuum jacket, or inert atmosphere can significantly increase the life.

11.2.4.5.1 Multilayer Insulation. As previously indicated, gold-coated film appears to be more resistant to moisture, but has less adhesion. Gold-coating film, therefore, would appear to be more satisfactory than aluminized film for feedline insulation, insulation around valving, and similar applications where possible contact with the atmosphere and moisture is most likely to occur.

The superior adhesion and abrasion resistance of aluminized film appears to make it more satisfactory for vacuum-jacketed tanks and for purged-tank insulation.

Dacron net is demonstrating superior environmental resistance in the tests currently being conducted in the contract, "Effect of Environment on Insulation Materials", NAS 3-14342. Therefore, dacron net may be the both satisfactory material for use with gold- and aluminized-film as a spacer and support material.

11.2.4.5.2 Foam Insulation. This insulation reusability is of major concern to NASA and contractor investigators, with considerable justification. Used as an internal insulation, it receives more protection from environmental effects but is subjected to liquid contact, slosh loading, etc. As an external foam, it is subjected to severe environmental conditions. Cracking can result in cryopumping with significant effects.

It is unlikely that a foam insulation can be employed that will last the lifetime of the shuttle. However, in aircraft practice, organics such as fuel-tank bladders (fuel-tank sealant in military aircraft) and interiors are replaced at intervals (based on lifetime constraints).

11.2.4.6 Fiberglass Tank Support Struts. A study of the fiberglass struts reusability was performed under Fiberglass Support for Cryogenic Tanks , NAS3-12037. There are sufficient cryogenic-tank support test investigations to indicate that fiberglass tank struts are capable of being (1) cycled to design loads and (2) unloaded at least 10,000 times in both tension and compression with design safety factors of 1.4. The critical failure mode is in tension loading. Failures normally occur in the warm end of the struts, since the tensile strength is less at the higher temperature.

The number of thermal cycles that the struts are capable of surviving without damage appears to be extremely large. Design practice is to match the thermal expansion characteristics of the fiberglass and end fittings.

11.3 TECHNOLOGY EVALUATIONS

Technology evaluations were performed with the objective of identifying the need for further technology improvements and developments. These evaluations were formulated to provide pertinent information relative to the importance of technology improvements and the extent of benefits that could be derived. The approach was to record technology information throughout the study as it was identified and to make the necessary analyses when the sensitivity and tradeoff studies were being performed.

This section of the report does not contain the application and the reusability analyses discussions.

11.3.1 Basic Data Requirements

In the performance of the evaluations, several items related to basic data were identified, as follows:

- Helium solubility in cryogenics
- Hydrogen flame data
- Fracture mechanics data
- General bellows data for cryogenic applications
- Organic materials lifetime data
- Cryogenic fluid capillary properties

11.3.1.1 <u>Helium Solubility in Cryogenics</u>. Data available regarding helium solubility in liquid oxygen, liquid hydrogen, and liquid nitrogen need to be expanded. Also, basic data are needed concerning the release of helium resulting from pressure drops, introduction into pumps, introduction into thrusters, etc. This information is needed in propellant acquisition device studies, fuel cell purging, pumping of helium-saturated cryogenics, etc.

11.3.1.2 Hydrogen Flame Data. There are very little data available regarding hydrogen flames from low-leakage sources. Data are needed to determine the conditions for supporting combustion from potential hydrogen-leakage areas, as a function of air and nitrogen flowrates over various leakage geometries. These data are necessary to determine methods of employing nitrogen purge for potential component leakage regions. Also, data are needed to establish confidence for elimination of purging from components.

11.3.1.3 Fracture Mechanics Data. The desired quantity of fracture mechanics data for shuttle cryogenic materials is not available. Fracture mechanics data for all alloys and conditions that might be employed in the shuttle could provide considerably more design confidence and lower design allowables.

11.3.1.4 General Bellows Data for Cryogenic Applications. A number of component failures in cryogenic applications are related to bellows. These include bellows as a part of feedline components, regulators, valves, etc. While considerable testing and analyses have been performed, there needs to be a centralized collection made of these data and additional testing performed to provide adequate parametric data, analytical techniques, etc. Lifetime (reusability) data should be established for a wide variety of applications.

11.3.1.5 Organic Materials Lifetime Data. As has been indicated in numerous places in this report, the lifetime of organic materials will be the limiting factors in many applications. The shuttle has uniquely imposed environments, which include severe launch conditions, periodic vacuum exposure, and periodic exposure to temperatures up to 350°F. From considerable experience with organic materials, the aircraft industry is capable of selecting proper electrical insulations, thermal insulations, plastics, etc.

The initiation of a "materials and processes" function for the shuttle, similar to that employed in aircraft, and the collection of required data should result in significant payoffs in the future design efforts. Component manufacturers will need considerable assistance in the selection of suitable organic materials.

11.3.1.6 Cryogenic Fluid Capillary Properties. Data are very limited regarding the capillary properties of cryogenic fluids. These data need to be expanded to improve analytical techniques.

11.3.2 Improvements in Analytical Techniques

Several areas requiring improvement in analytical technique were determined as follows:

- Improvement in pressurization analytical techniques
- Improvement in cryogenic fluid stratification analytical techniques
- Analysis of insulation purging

11.3.2.1 Improvements in Pressurization Analytical techniques. Pressurization in subcritical cryogenic supply systems represents a major weight factor. Errors in the optimization of the pressurization system can be more significant than errors in the optimization of the insulation system. Development of analytical techniques and support test data has been severely neglected. The pressurization analytical techniques are related to the stratification analyses improvements subsequently discussed and ultimately must be coupled with these results.

11.3.2.2 Improvements in Cryogenic Fluid Stratification Analytical Techniques. The stratification of cryogenic fluids under acceleration and heating can have significant effects upon design. Stratification is closely coupled with the pressurization analyses. Coupling with the pressurization analyses can be particularly significant when the sidewall heating rates are low, as in a multilayer insulated tank.

Programs need to be initiated that provide for analytical improvements with related large-scale testing.

11.3.2.3 Analysis of Insulation Purging. Even if vacuum jacketing is used extensively on the shuttle, insulation purging will be required for a number of applications. Insulation-purging analyses relate to assurance that (1) atmospheric gases are removed, (2) inert atmosphere is maintained after the system is filled with cryogenics and(3) the venting processes are functioning during ascent. Improvements in the analytical techniques are needed to provide for the design of purging and purge vent systems for a variety of conditions. In some of the relatively small volumes to be purged, the desired sizing of the vents would be small in comparison with the mean free path of the gas molecules at low pressure.

11.3.3 Mechanical and Electrical Components (Instrumentation and Controls Not Included)

The mechanical and electrical components (other than instrumentation and controls) generally were found to require little technology advancement. With the exception of several major components, most of the modifications would fall into the category of design improvements rather than technology advancements.

11.3.3.1 Cryogenic Pumps.

11.3.3.1.1 Attitude Control Propellant Supply. The pumps for the Attitude Control Propellant Supply subsystem have been recognized as a technology advancement requirement for the last two years. Work is currently underway under "APS LO_2 and LH_2 Turbopump Assemblies", NAS 8-27784, being performed by Rocketdyne Division of North American Rockwell.

It is recognized that the severe requirements for this turbopump can be reduced by the acceptance of accumulator weight penalties. Some tradeoffs in this manner will likely be necessary to offset high development costs.

In this study, an examination was made of the effects of turbopump start transient on acquisition device sizing. The acquisition device was the type discussed for the integrated OMPS/ACPS system. It is a "gallery" type device, which is generally accepted as the principal candidate for this application.

The current RL-10 start transient was used as the model of a typical "severe" start transient. Severe effects from the start transient are normally near the end of the transient.

In a device of this type, it is necessary to consider the gas "breakthrough" of a screen that is in gas, while the flow is being supplied from a screen in liquid that is some distance upstream from the screen in the gas. Typical geometries examined are presented in Fig.11.3-1.

The results of the analyses are presented in Fig. 11.3-2. As may be seen from these analyses, the required head differential pressure capabilities must be large, even for the very large gallery line diameters considered.

In order to lower the sizes of the acquisition device lines, the turbopump will have to be designed to have a smooth, almost linear, start transient that will reduce the fluid accelerations. This will undoubtedly require some type of throttling of the turbine.

11.3.3.1.2 <u>Auxiliary Power Unit Supply</u>. If the APU supply is stored subcritically and separately from the other subsystems, a pump is required that is capable of being operated continually and "dead headed" when flow is not required.

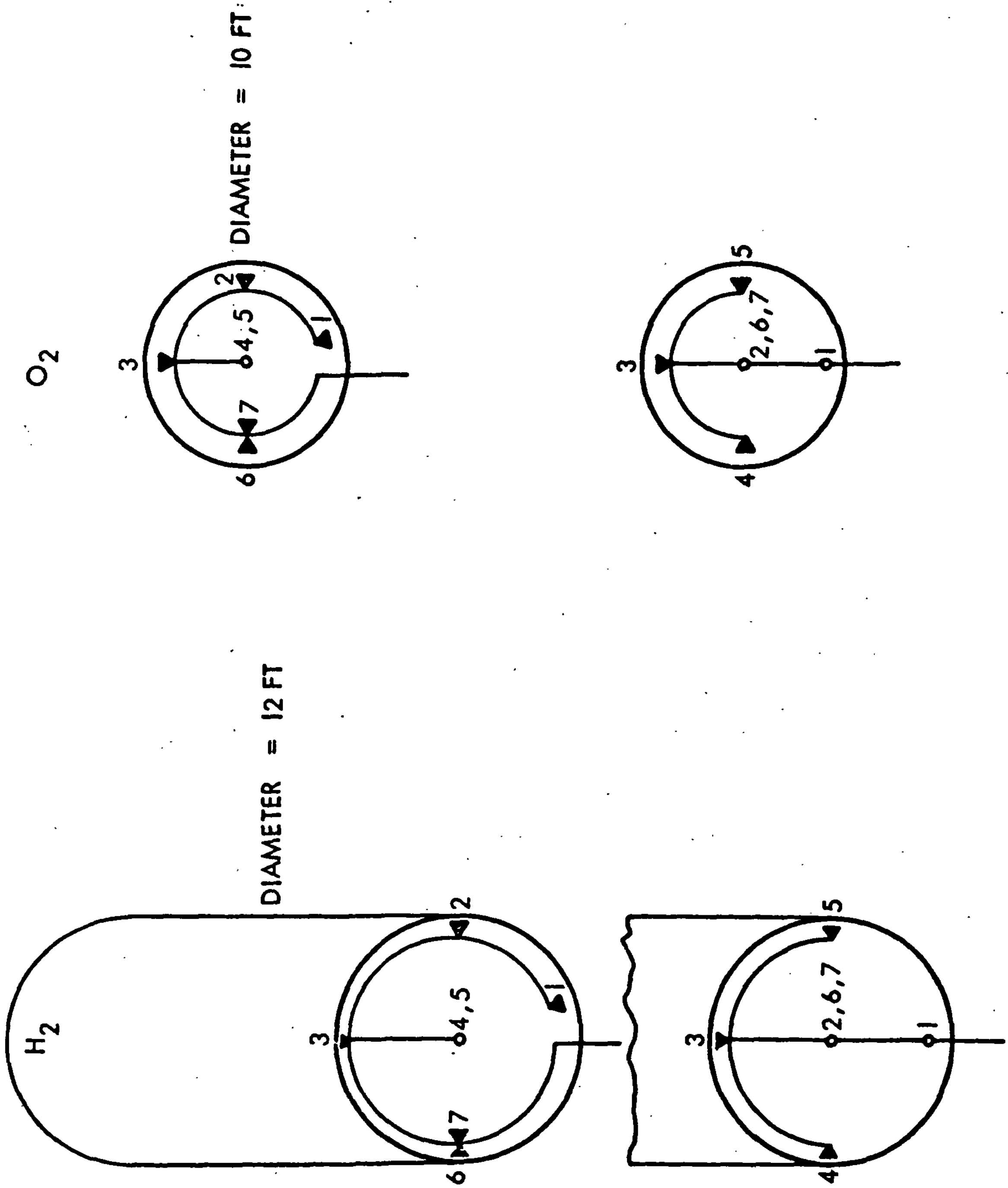

Fig. **11.3-1** Propellant Acquisition Device Configuration

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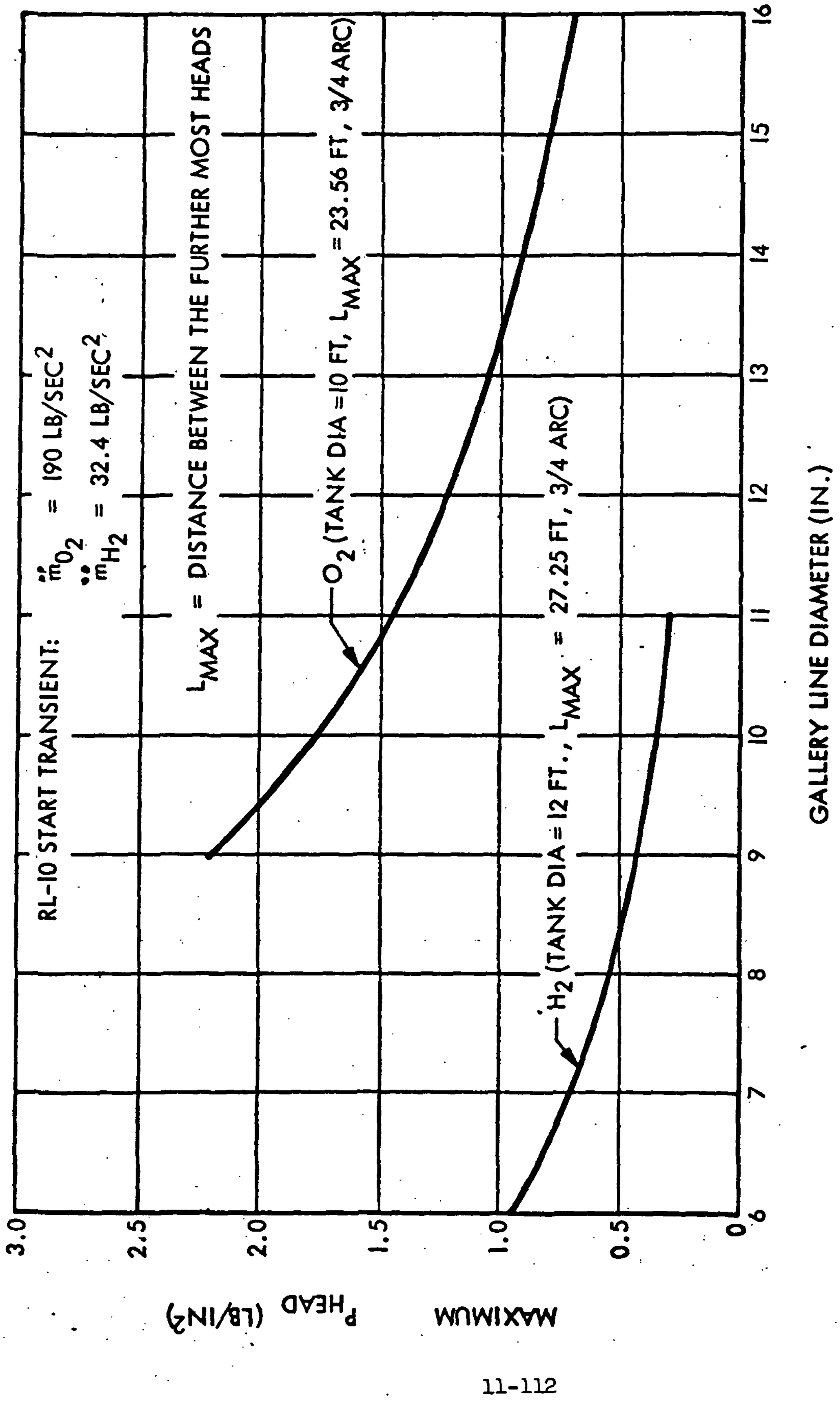

D04715

Fig. 11.3-2 Required Head Differential Capability versus Gallery Line Diameter

11.3.3.2 Cryogenic-Cooled Electrical Motors. The cryogenic-cooled electrical motors were examined, and each offered potential applications. As shown, electrical motors may even be applicable to the ACPS pumps. Further investigation into the employment of the cryogenic-cooled electrical motor is desirable. Technology programs are needed to further define the motors and development requirements.

11.3.3.3 Valves and Regulators. The valves and regulators examined by AiResearch and LMSC indicated little requirements for technology advancements. Most of the requirements are for design improvements and testing to establish lifetimes.

One area for specific improvement is to incorporate fail-operational/fail-safe provisions into the valve actuators. There are a number of applications for latching solenoid actuators with fail-operational/fail-safe capability.

One class of valves significantly lagging in technology is disconnects. The disconnects for the cryogenic supply systems are generally bulky; thermal aspects need improvement to reduce icing and heat input. There is some doubt regarding the reusability of current disconnects.

11.3.4 Instrumentation and Control

As a class of components, the instrumentation components generally have lower service life and a higher probability of failure than other components.

11.3.4.1 Pressure Switches. Pressure switches with increased lifetime need to be developed. These are required for both oxygen and hydrogen systems.

11.3.4.2 Liquid-Hydrogen Pressure Transducers. A satisfactory pressure transducer that will function immersed in liquid hydrogen is required. The integrated systems necessitate pressure monitoring without liquid orientation, and this is currently not satisfactory with existing transducers.

11.3.4.3 Leakage Detection Devices. A family of leakage-detection devices is required to detect body gas losses and safety hazards. Sonic devices may be satisfactory for low leakages.

11.3.4.4 Temperature Control of Venting. As was presented in previous discussions, control of venting by liquid temperature rather than by ullage pressure would allow much more control flexibility. This will require technology advancement in the temperature sensors and the control logic.

11.3.5 Tankage

Tankage has not been identified as a significant technology problem because of the extensive experience that has been accumulated and the design techniques available. However, two areas have been selected for technology advancement:

- Composite Tankage
- Vacuum Shell

11.3.5.1 Composite Tankage. The importance of the accumulators in the system optimizations has been presented in previous evaluations. The lowering of the accumulator weights can reduce the turbopump requirements in the ACPS subsystem.

High-strength, low-weight tanks are probably best achievable with metal-lined filament-wound composites. Cryogenic-formed steel (Arde process) appears to be very attractive for inert gas and oxygen storage. Other composite tank approaches should be examined.

Tests are required to determine the cycle lifetime of acceptable composite tank approaches.

11.3.5.2 Vacuum Shell. The major improvement required in vacuum shells is weight reduction - with design confidence. If vacuum shells are required for the orbit maneuvering propellant supply subsystem, these are of considerable size and weight, and weight saving through technology advancement can be substantial.

11.3.6 Feedlines and Feedline Components

Existing stainless steel and Inconel lines do not require significant technology advancement. The problems are principally related to design problems.

11.3.6.1 Aluminum Feedlines. Significant weight savings are possible through the use of aluminum feedlines. However, the expansion joints must be of stainless steel or Inconel and joining with the aluminum is required.

Technology advancement and extensive cryogenic testing are required for the development of these composite feedlines.

11.3.6.2 Vacuum Sealoff Valves. Vacuum sealoff valves have been identified for technology development. The seats in the valves must be improved to hold vacuum for extended periods under flight environments.

11.3.7 Propellant Acquisition

Propellant acquisition has been identified as the major shuttle problem related to cryogenics. The development of a satisfactory device is necessary for the attitude control propellant supply and other subsystems, dependent upon the degree of integration. Considerations associated with generating this conclusion are:

- The shuttle adverse acceleration requirements are high, probably resulting in multiple screens.
- The required start transients are severe, resulting in large device pressure drops.

- Gas ingestion into the devices will be a difficult problem and complete exclusion of gas may not be possible.

11.3.8 Insulation

Multilayer insulation was not identified as requiring significant technology development.

11.3.8.1 Groundhold, Ascent and Reentry Insulation. The groundhold, ascent, and reentry insulations (which include foams, purged batting, and gas barriers) require significant development. The problems related to reusability have been previously discussed.

11.3.8.2 Feedline Insulation. The development of effective feedline insulation systems that are removable is desirable. For most applications, this system would require multilayer and foam combined in an optimum fashion. Purging of the insulation to remove the atmosphere is a very likely requirement.

11.3.8.3 Breathing Insulation System. Some of the multilayer insulation applications do not require helium or nitrogen purging during reentry. However, it is considered desirable to remove contamination and moisture. A drier and filter system could satisfy the requirements, allowing the insulation to "breath" without contamination.

11.3.9 Subsystem Technology Development

Several technology developments at the subsystem level were identified as follows:

- Liquid/liquid attitude control
- Electrical integration of the cryogenic subsystems
- Subsystem integrated control
- Cryogenic cooling

11.3.9.1 <u>Liquid/Liquid Attitude Control</u>. The Liquid/Liquid Attitude Control Propellant Supply subsystem has been shown to be a potentially satisfactory subsystem. The requirements for subsystem components are much less severe than for the Gas/Gas Attitude Control Propellant supply.

Technology examinations of this system are justified on the basis of an alternate ACPS development. The component development requirements of the Gas/Gas system may prove to be too costly. The Liquid/Liquid system indicates potentially a much less development cost.

11.3.9.2 <u>Electrical Integration of the Cryogenic Subsystems</u>. The possibility of employing electrical motors for pump power, in addition to the other electrical requirements of the subsystems, indicates that technology examinations are justified to evaluate integration of the electrical systems.

11.3.9.3 <u>Subsystem Integrated Control</u>. Considerations of subsystem and integrated system control early in the shuttle program will provide significant guidance to the subsystem developments. The logical starting point is with the ACPS subsystem; the control system evaluations would then be expanded to the entire integrated system.

11.3.9.4 <u>Cryogenic Cooling</u>. The cryogenic-cooling task currently being conducted under this contract is indicating that radiator replacement or supplementation is promising. Technology evaluations of the most promising approaches should continue towards the development of a suitable integrated cryogenic-cooling system.

Section 12
REFERENCES

This section of the Interim Report is provided to consolidate reference information cited in the discussions and to provide general information. The references, listed on pages 12-12 through 12-20, are numbered according to the sections in which they appear.

12.1 GENERAL INFORMATION

The Task Reports are referenced in most of the sections. Brief listings of the information which is provided in the Task Reports are presented in Tables 12-1 through 12-6. These are the current contents of the Task Reports and will be modified as more data are generated.

Table 12-1

PROGRAM/PROJECT MANAGEMENT TASK REPORT

OUTLINE OF CONTENTS

1 LIAISON ENGINEERING

- 1.1 Phase B Contracts Interfaces and Data Sources
- 1.2 Supporting Technology Contracts
- 1.3 Related Technology Contracts
- 1.4 Source References

2 REPORTS

- 2.1 Monthly Progress Reports (three volumes)
- 2.2 Status Reviews/Minutes (two volumes)
- 2.3 Subcontractor Reports (five volumes)
- 2.4 Other volumes will be added, as required

Table 12-2

MASTER INTEGRATED SYSTEMS TASK REPORT

OUTLINE OF CONTENTS

Table 12-2 (Cont.)

9.3 Thermal Protection
9.4 Fluid Dynamics
9.5 Thermal Control and Fluid Conditioning
9.6 Expendables

10 REFERENCES

11 APPENDIXES

Table 12-3

INTEGRATED SUPPLY SYSTEMS TASK REPORT

OUTLINE OF CONTENTS

1 INTRODUCTION

2 REQUIREMENTS AND CRITERIA

- 2.1 Life Support Supply System Requirements and Duty Cycles
- 2.2 Power Generation Reactant Supply System Requirements and Duty Cycles
- 2.3 Propulsion Supply System Requirements and Duty Cycles
- 2.4 Safety and Abort Criteria

3 INTEGRATED SYSTEM DEFINITION

4 REFERENCES

5 APPENDIXES

Schematic Symbols List

Comp Symbols List

Table 12-4

PROPELLANT SUPPLY SYSTEMS TASK REPORT

OUTLINE OF CONTENTS

1 INTRODUCTION

2 REQUIREMENTS AND CRITERIA

- 2.1 Orbit Injection Supply System Requirements and Duty Cycles
- 2.2 Orbit Maneuvering Supply System Requirements and Duty Cycles
- 2.3 Attitude Control Propulsion Supply System Requirements and Duty Cycles
- 2.4 Airbreathing Engine Fuel Supply System Requirements and Duty Cycles
- 2.5 Purge, Inerting, and Pneumatic Supply System Requirements and Duty Cycles

3 ORBIT INJECTION SUPPLY SYSTEM DEFINITION

- 3.1 Definition of Candidate Concepts
- 3.2 Candidate Systems
- 3.3 System Tradeoff Results

4 ORBIT MANEUVERING SUPPLY SYSTEM DEFINITION

(Subheadings same as 3.0 above)

5 ATTITUDE CONTROL PROPULSION SUPPLY SYSTEM DEFINTION

(Subheadings same as 3.0 above)

6 AIRBREATHING ENGINE FUEL SUPPLY SYSTEM DEFINITION

(Subheadings same as 3.0 above)

7 PURGE, INSERTING, PNEUMATIC SUPPLY SYSTEM DEFINITION

(subheadings same as 3.0 above)

8 MODULE AND COMPONENT PARAMETRIC DATA

- 8.1 Storage Tanks and Components
- 8.2 Fluid Delivery Components

9 SYSTEMS ANALYSES

- 9.1 Structural Considerations
- 9.2 Thermodynamics
- 9.3 Thermal Protection Analysis
- 9.4 Fluid Dynamics

Table 12-4 (Cont.)

Table 12-5

POWER GENERATION REACTANT SUPPLY SYSTEM REPORT

OUTLINE OF CONTENTS

1 INTRODUCTION

2 REQUIREMENTS AND CRITERIA

- 2.1 Fuel Cell System Requirements and Duty Cycles
- 2.2 Auxiliary Power Unit System Requirements and Duty Cycles

3 FUEL CELL SUPPLY SYSTEM DEFINITION

- 3.1 Basic Fuel Cell Considerations
- 3.2 Definition of Candidate Systems
- 3.3 Candidate Systems
- 3.4 Fuel Cell Supply Tradeoff Studies

4 AUXILIARY POWER UNIT SUPPLY SYSTEM DEFINITION

- 4.1 Auxiliary Power Unit Considerations
- 4.2 Definition of Candidate Concepts
- 4.3 Candidate Systems
- 4.4 Auxiliary Power Unit Supply Tradeoff Studies

5 MODULE AND COMPONENT PARAMETRIC DATA

- 5.1 Storage Modules and Components
- 5.2 Fluid System Components

6 SYSTEMS ANALYSES

- 6.1 Hydrazine Auxiliary Power Unit Supply Analyses

7 REFERENCES

8 APPENDIXES

Table 12-6

LIFE SUPPORT SUPPLY SYSTEM TASK REPORT

OUTLINE OF CONTENTS

Table 12-6 (Cont.)

7 APPENDIXES

Schematic symbols list

Math symbols list

NOTE:

Data currently being developed under Task 1(a), Cryogenic Cooling, will be incorporated in this Task Report

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12.2 SECTION 5 REFERENCES

No.	Title
5-1	LMSC-A989142 Lockheed Missiles & Space Co., "Study of Alternate Space Shuttle Concepts", NAS 8-26362, 4 June 1971
5-2	PWA PDS-4198, Pratt & Whitney Aircraft, "The RL-10 Engine for Advanced Space Propulsion", 21 Dec 1971
5-3	SDB 2.3.1.3, North American Rockwell Corporation, "System Data Book, Orbit Maneuvering System for Space Shuttle Program."
5-4	MDC E0189, McDonnell-Douglas Corporation, "Space Shuttle Program Phase B Systems Study Data Book - Volume I," 23 Apr 1970, Revised 1 Jun 1970
5-5	McDonnel Douglas, Space Shuttle Propulsion Mid-Term Review Splinter Meeting, 10, 11 Dec 1970
5-6	SV 71-4 McDonnel Douglas, "Space Shuttle Phase B 180 Day Review", 13 Jan 1971
5-7	SBD 2.3.1.2, North American Rockwell Corporation, "System Data Book, Orbiter Main Propulsion System for Space Shuttle Program."
5-8	Spec 2289, "Preliminary Model Specification, Rocket Engine, Liquid Propellant, Pratt & Whitney Aircraft Model RL10A-3-3A," 21 Apr 1969
5-9	MSC-02542, "Typical Shuttle Mission Profiles and Attitude Timelines," Vol I - Space Station Resupply Missions, 23 Jun 1970
5-10	McDonnell-Douglas Corporation, "Space Shuttle Phase B Quarterly Review Presentation Charts, 1 Oct 1970
5-11	RFP 10-8423, NASA OMSF, "Space Shuttle Vehicle Definition/Design Study," 19 Feb 1970

NO.	Title
5-12	NASA ICD No. 13 M 15000-A, "Space Shuttle Interface Control Document."
5-13	SDB 2.3.1.4, North American Rockwell Corporation, "System Data Book, Attitude Control Propulsion System for Space Shuttle Program."
5-14	NASA, "Space Shuttle Vehicle Description and Requirements Document," (APS Definition), 1 Oct 1970
5-15	SDB 2.3.6.1, North American Rockwell Corporation, "System Data Book, Power Generation System for Space Shuttle Program."
5-16	Pratt & Whitney Aircraft, "Space Shuttle Fuel Cell Systems" Technical Briefing Handout to LMSC, 2 Dec 1970
5-17	General Electric, "Fuel Cell Technology Program for Future Manned Space Flights", Technical Briefing Handout, 28 Oct 1970, presented toLMSC by L. J. Nuttall on 8 Jan 1971
5-18	North American Rockwell Corporation, "Space Shuttle Orbiter Environmental Control and Life Support System Synthesis" prepared by W. F. Dyer, Dec 1970
5-19	North American Rockwell Corporation, " Documentation for Space Shuttle 90 Day Review, Team 7 - Environmental Control and Life Support, 1 Oct 1970

12.3 SECTION 9 REFERENCES

No.	Title
9-1	W. G. Steward, R. V. Smith, and J. A. Brennan, "Cooldown Time for Simple Cryogenic Pipelines," Proceedings of the 10th Midwestern Mechanics Conference, Aug 1967
9-2	LMSC-K-14-67-3, Lockheed Missiles & Space Company, "Cryogenic Container Thermodynamics During Propellant Transfer," Final Report, Contract NAS 8-20362, 31 Oct 1967
9-3	J. A. Brennan et al, "Cooldown of Cryogenic Transfer Lines - An Experimental Report," NBS Report 9264, NBS-CRL, Boulder, Colo, Nov 1966
9-4	Lockheed Missiles & Space Co., "Program 827 Hot Pump Restart Limits", IDC, R. D. Crozier to R. W. Johnson, 22 Feb 1968, (See following pages).

INTERDEPARTMENTAL COMMUNICATION

TO	R. W. Johnson	DEPT./ORGN.	62-59	BLDG./ZONE	154	PLANT/FAC.	1	DATE	22 Feb 68
FROM	R. D. Crozier	DEPT./ORGN.	62-22	BLDG./ZONE	154	PLANT/FAC.	1	EXT.	28871

SUBJECT: PROGRAM 827 HOT PUMP RESTART LIMITS

Ref: (a) Report "Restart Boilout Preliminary N_2O_4 Static Test Results", dated 19 February 1968

Near the end of December, Propulsion Systems was requested to evaluate the effect of 260°F propellant pump temperatures on the restart reliability of the Program 827 third burn. During this period, restart boilout tests were being conducted with the Improved Agena propellants to define the 8533 engine turbo pump thermal design requirements. The tasks were integrated so that the 1964 SS-01B hot pump test data could be included with the Improved Agena test data to develop a boilout model to be used for 8533 turbopump thermal design and for extrapolation of the SS-01B data to the Program 827 flight thermal conditions. This effort has been accomplished and it is concluded that the predicted 260°F Program 827 temperatures are in excess of values allowable for reliable third burn restart.

The boilout model developed is presented in Reference (a) and utilizes both the SS-01B IRFNA/UDMH and Improved Agena N_2O_4 test data. The model assumes that the dominant boilout criteria is the degree of pump superheat. Superheat is defined as the pump housing temperature excess above the propellant boiling point at the specified tank pressure. A summary of the results is presented in Figure 12-1. For the Program 827 propellants, it can be seen that no pump boilout occurs below a superheat of approximately 30°F. Between 30°F and 75°F the pumps are filled with propellants by tank pressure as the propellant isolation valves (PIVs) open prior to engine restart. After filling, the propellants gradually boil and are expended from the pump producing a vapor locked condition which precludes reliable restart. Initiation of engine operation during the early portion of the gradual boilout suppresses boiling and allows normal engine restart.

For superheats above 75°F, boilout occurs so rapidly that a combination of engine and PIV sequencing will not reliably suppress boiling and initiate normal flow to the thrust chamber (restart). The minimum Program 827 third burn tank pressure is approximately 18 psia. With a pump temperature of 260°F the data point lies on the 100°F superheat line of Figure 12-1. The test data presented in Figure 12-1 provides substantiation of only a narrow portion of the boilout model. With the limited data available, it is concluded that extrapolation of the satisfactory restart region should be limited to the bracketed portion of the 75°F superheat line. For Program 827, this region can be attained by levering the maximum oxidizer pump housing temperature to about 230°F.

Form LAC 201

Elevating the tank pressure to 30 psia will return the 827 point to the 75°F superheat line but additional pressure must be added to account for uncertainties in the model extrapolation to this new region. Although the tank pressure elevation hardware requirements can be defined it is not known what is required to lower the maximum pump temperature. It is recommended that additional thermal analyses be conducted to determine the thermal alternatives.

R. D. Crozier, Manager
Propulsion Systems

RDC/SCD:t

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R. Winquist	65-10/154
E. Yoder	62-59/154
D. Youre	62-59/154

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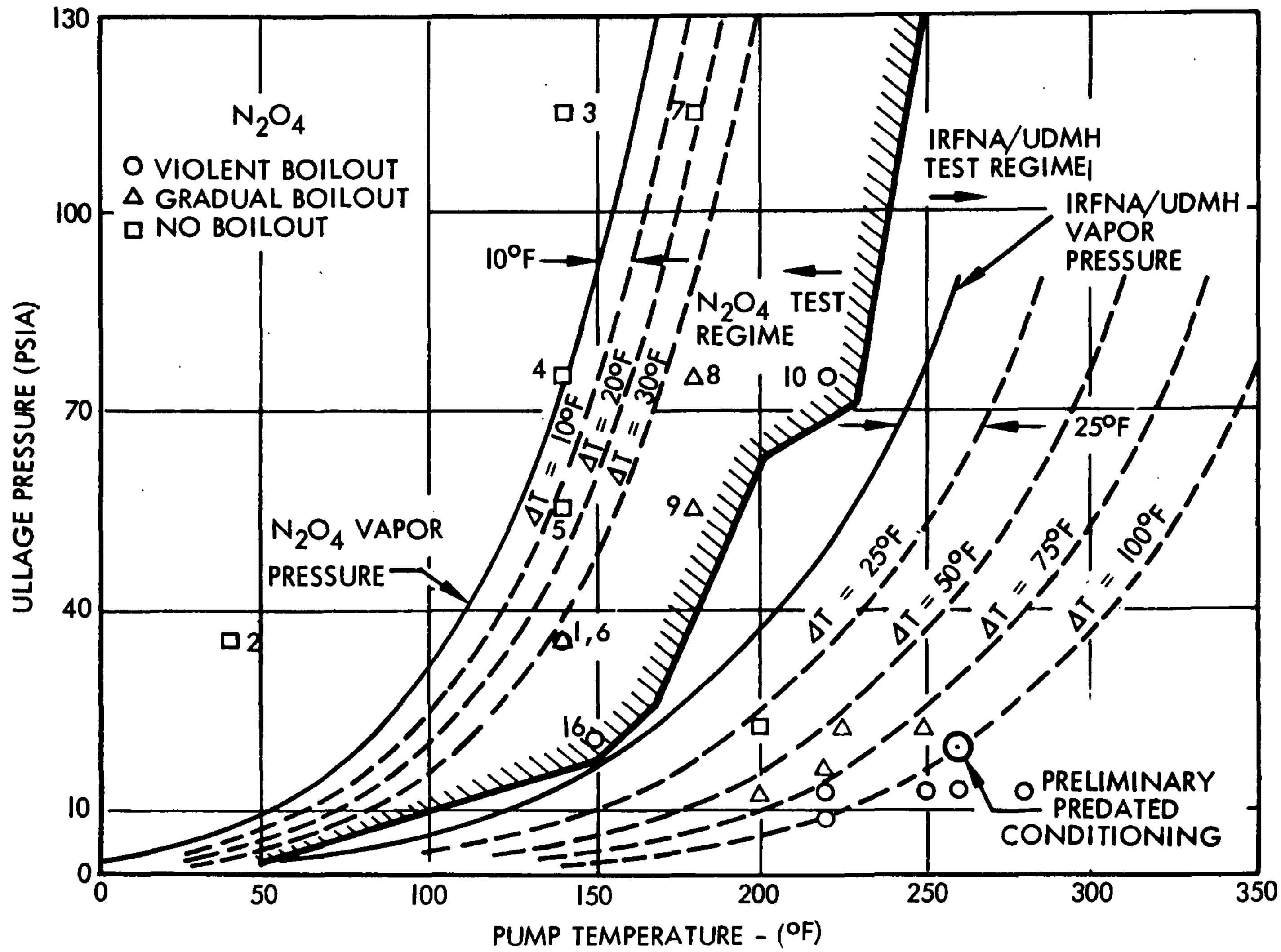
FIGURE 12-1
SUMMARY OF HOT PUMP BOILOUT TESTING WITH N_2O_4 AND IRFNA/UDMH



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12.4 SECTION 11 REFERENCES

No.	Title
11-1	List of Manufacturers Supplying Component Data

In addition to the subcontract with AiResearch, a number of manufacturers supplied component data without charge. Their assistance was important to the accomplishment of this contract.

Valves, Regulators, etc.

(1) Calmec, Division of Ametek
(2) Parker, Division of Parker Hannifin
(3) Sterer

Tankage

(1) Arde, Inc.
(2) Aerojet General

Feedlines and Feedline Components

(1) Ametek/Straza Corp.
(2) Arrowhead Bellows Mfg. Co.
(3) Solar Mfg. Co.
(4) Flexible Metal Hose Co.
(5) Stainless Steel Products Corp.
(6) Aeroquip Marmon

Instrumentation

(1) Bell and Howell

(2) Bourns, Inc.

(3) Travis Corp.

(4) Custom Component Switches, Inc.

(5) Kratos Instruments

(6) Thermal Systems, Inc.

(7) Bendix - Instruments and Life Support Division

(8) Simmons Precision Products

(9) Statham

(10) Giannini Controls

11-2 SD 68-490, North American Rockwell Corporation, "A Second Look at the Exponential Assumption for Reliability Estimating", Jul 1968

12.5 APPENDIX A REFERENCES

No.	Title
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A-2	70-6810(2), AiResearch Manufacturing Company, Space Shuttle APU System Study Contract NAS 3-14408 System Selection Review", 15 Dec 1970
A-3	70-7014, AiResearch Manufacturing Company, Preliminary Design of an Auxiliary Power Unit (APU) for the Space Shuttle" Contract NAS 3-14408, 15 Dec 1970
A-4	BC 70-73, Rocketdyne, North American Rockwell, "Space Shuttle Auxiliary Power Unit (APU) - Preliminary System Study
A-5	BC 70-175, Rocketdyne, North American Rockwell, "Space Shuttle Auxiliary Power Unit (APU) Phase 1 Summary", 18 Dec 1970
A-6	BC 70-116, Rocketdyne, North American Rockwell, "Space Shuttle Auxiliary Power Unit (APU) Phase 1 Summary, Supplementary Data", 18 Dec 1970.